Jet Propulsion Laboratory
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Intensity Mapping of Cosmic Structures

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Nick Luciw, Niels Oppermann, Ue-Li Pen (CITA),
Jeff Peterson (CMU), Tabitha Voytek, Yi-Chao Li (UKZN)
Chris Anderson, Peter Timbie (U. Wisc)

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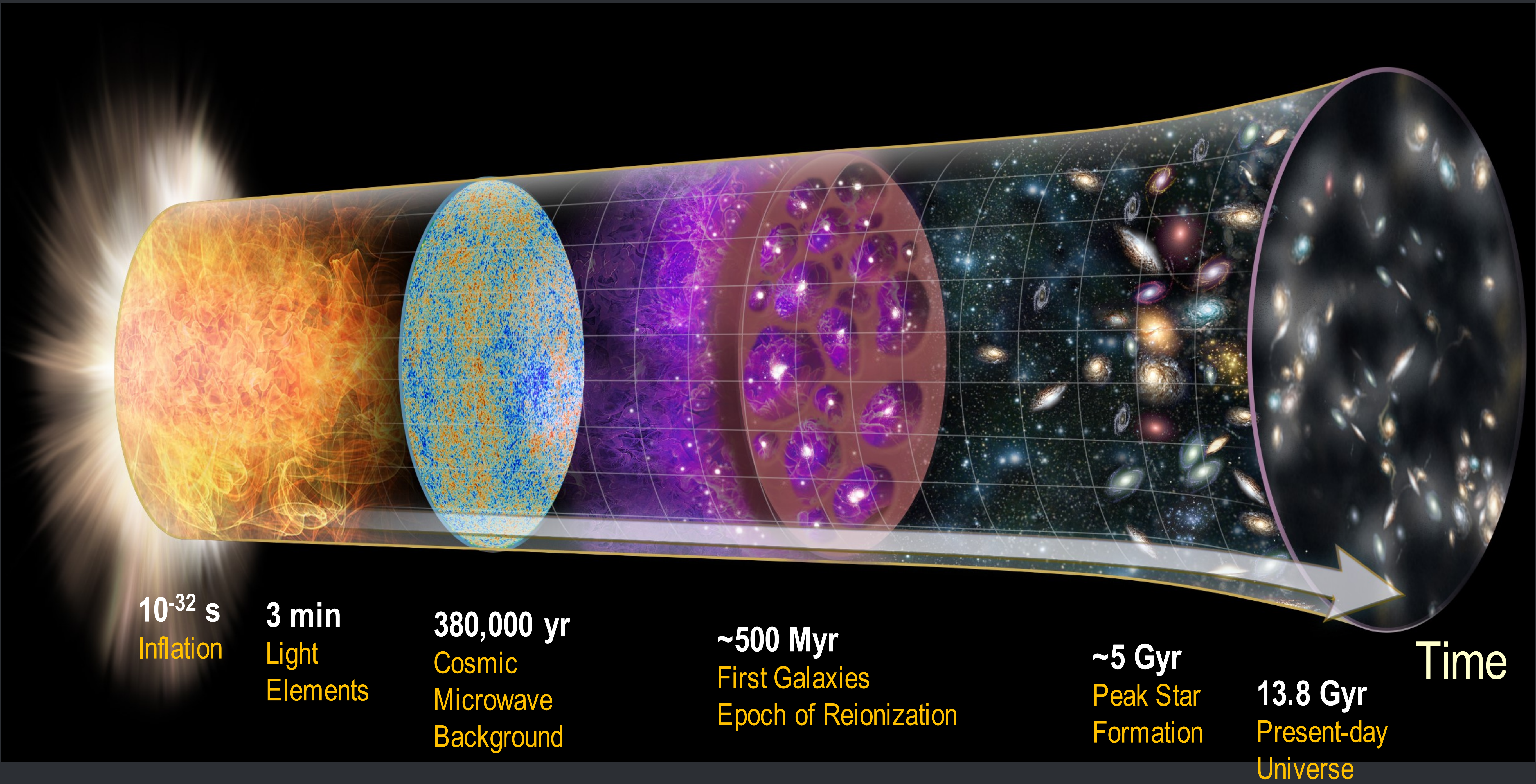
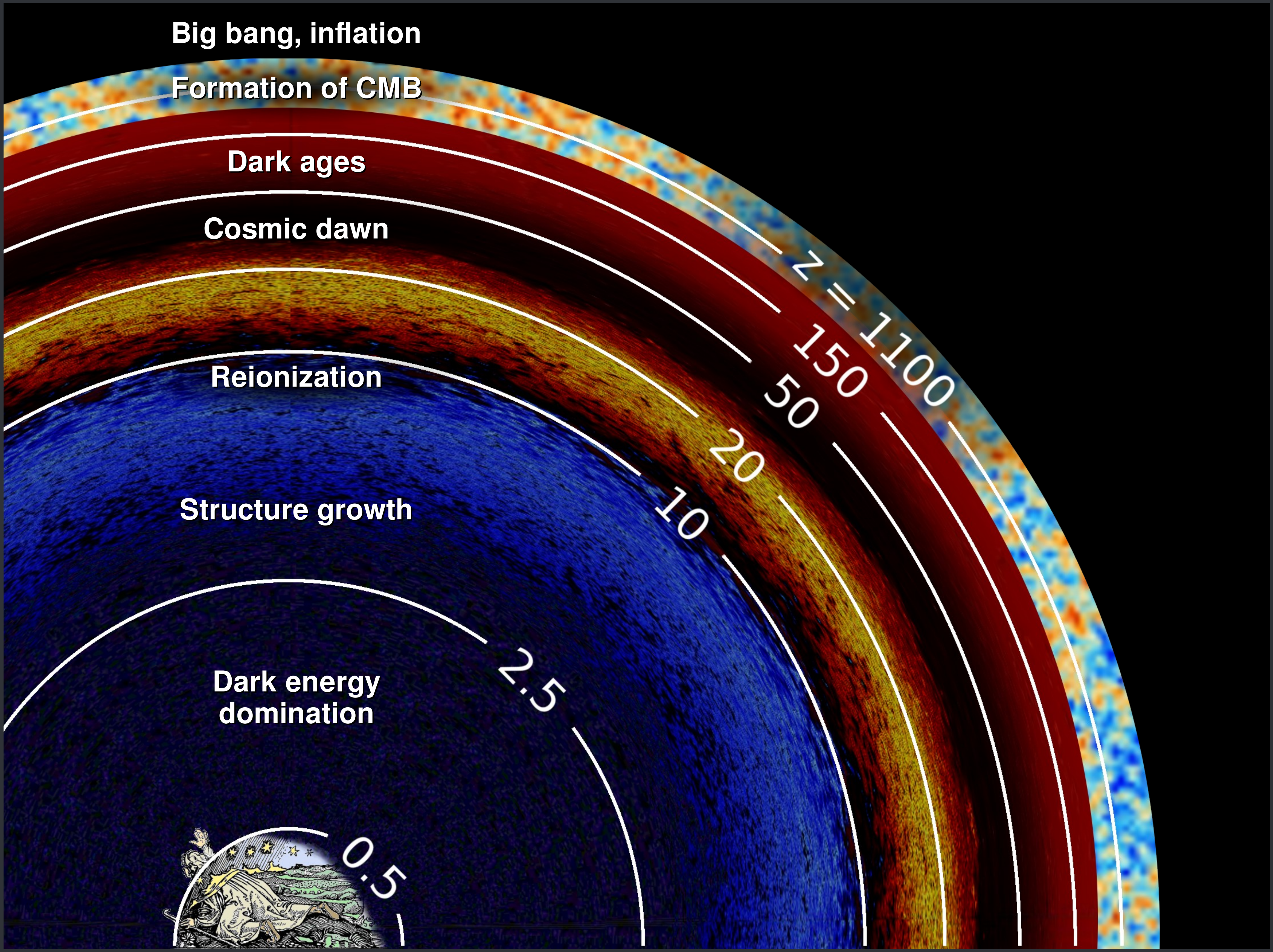
Jonathan Hunacek, Roger O'Brient, Jason Sun, Bade Uzgil (Caltech/JPL)
Patrick Koch, Chao-Te Li (ASIAA), Mike Zemcov (RIT), Dan Marrone (Arizona)
Asantha Cooray, Yan Gong (UCI)

The Observable Universe



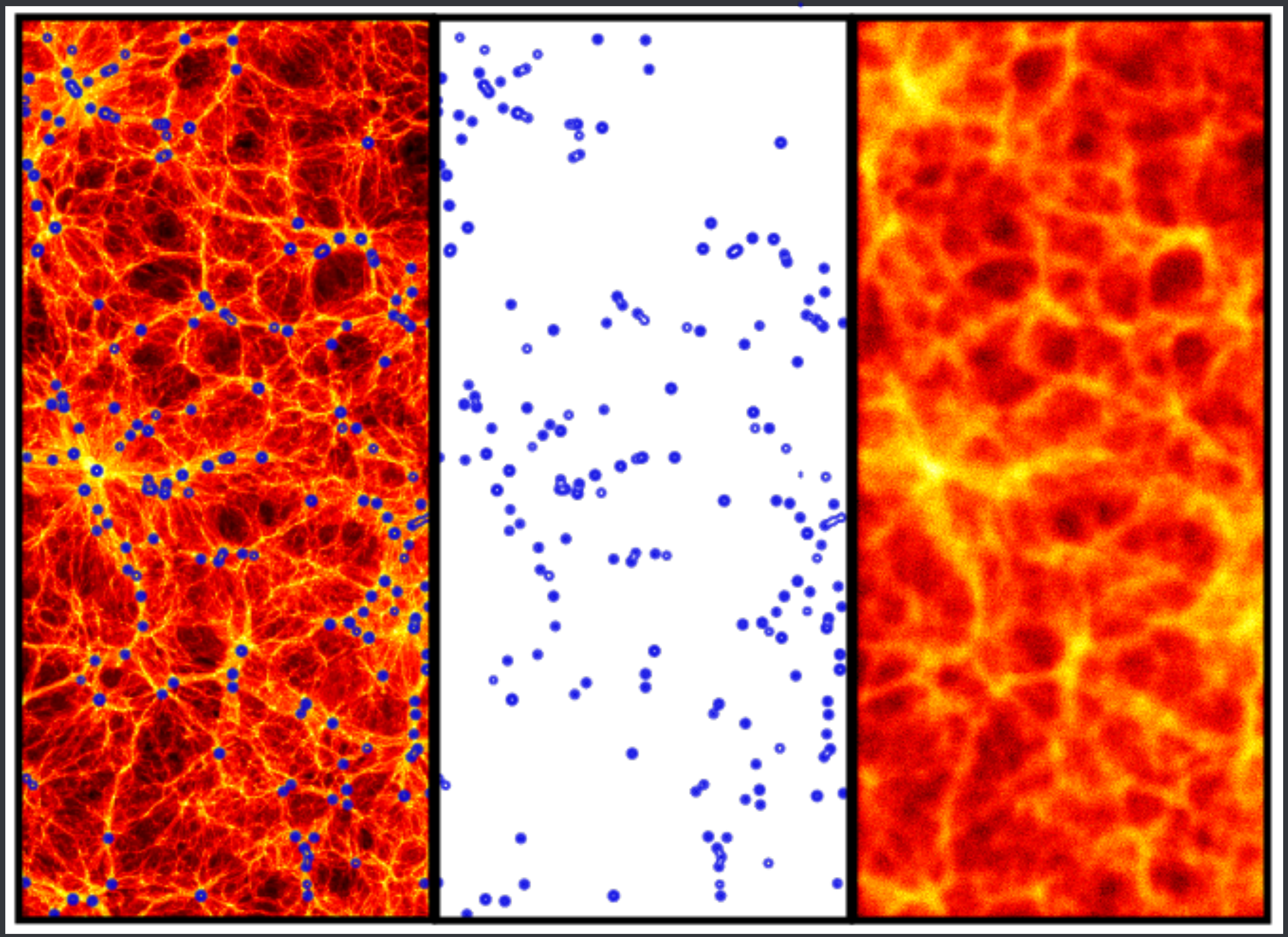
SPHEREx

Intensity Mapping of Cosmic Structures



Courtesy Cynthia Chiang

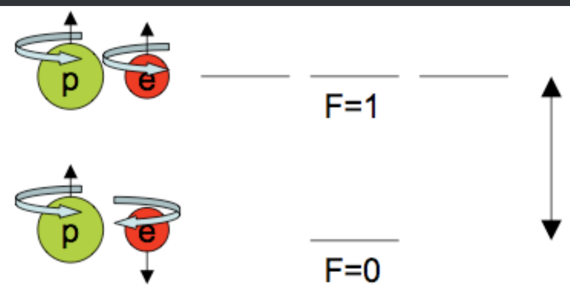
Line Intensity Mapping (IM)



courtesy of Phil Korngut (Caltech)

- "Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008):
  - Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain high frequency resolution thus redshift information
- Measure brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: economical, large survey volumes
- Confusion-limited. Foreground-limited.

The 21cm Line



$$\Delta E = \frac{4}{3}\alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9\mu\text{eV} = h(1420\text{MHz})$$

$$\lambda = 21\,\text{cm}$$

Courtesy C. Hirata

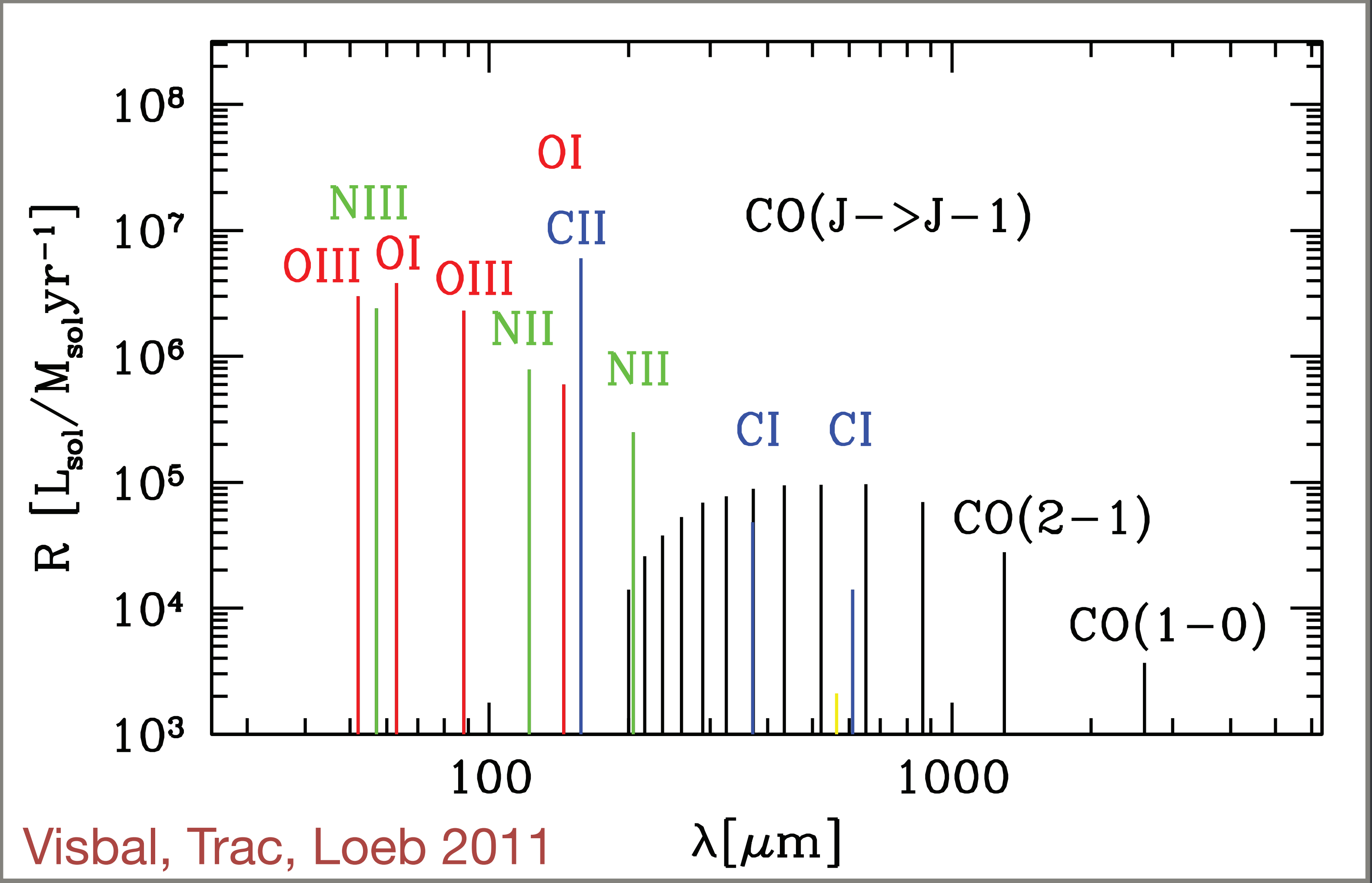
$$\frac{n_{F=1}}{n_{F=0}} = 3e^{-\Delta E / kT_s}$$

- Neutral hydrogen: most abundant baryonic element in the Universe.
- 21cm radiation: ground state spin-lip hyperfine transition of neutral hydrogen
- Optically thin along most line of sight
- Can be observable up to z~150, in emission or absorption against the CMB background:
    - $T_{spin} < T_{cmb}$: absorption (~15 < z < ~150)
    - $T_{spin} > T_{cmb}$: emission (z < 10)
- Expressed in terms of brightness temperature:

$$\Delta T = \frac{3 n_{\rm HI} \lambda^3 T_*}{32\pi H \tau_{1\to 0}(1+z)}\left(1 - \frac{T_{cmb}}{T_s}\right)$$

$$= 180\,(1+\delta)\left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5}\ \mu\text{K}$$

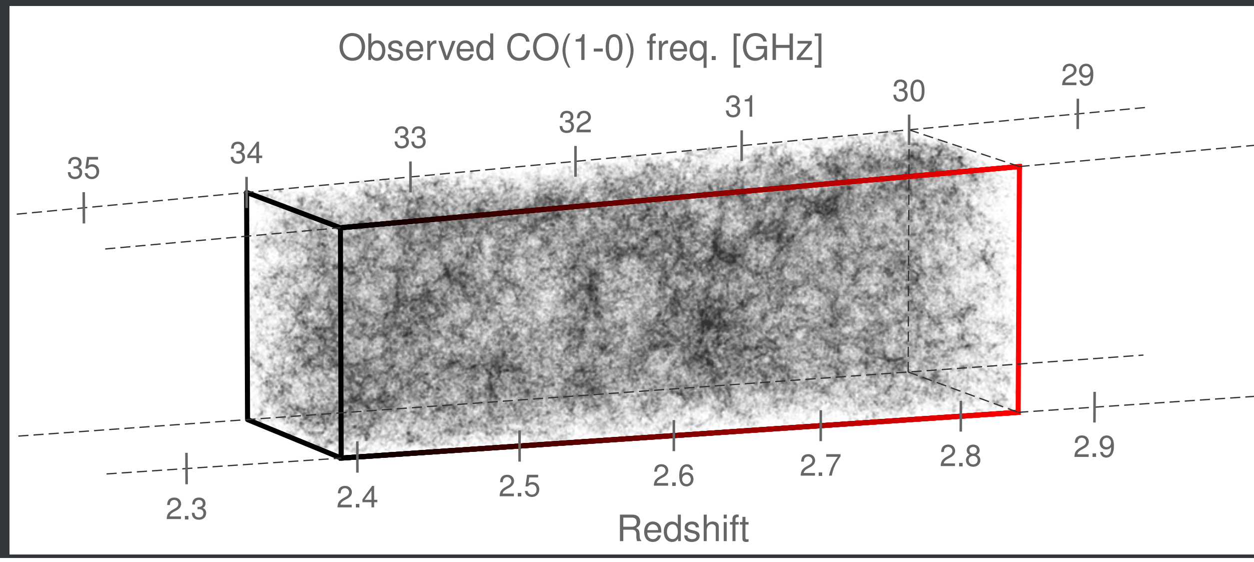
And all other spectral lines



Visbal, Trac, Loeb 2011

- CO IM - CO rotational lines (CO(1-0) at 115 GHz rest frame): Righi+ 08, Visbal & Loeb 2010, Carilli 2011, Gong+11, Lidz+11, Pullen+13, Breysse+14, Breysse+15, Li+ 15, Mashian+ 15, Keating+15, Keating+16)
- [CII] IM - singly ionized carbon (158 µm rest frame): Gong+12, Silva+14, Yue+ 15, Serra+16, Cheng+16
- Lyman-alpha IM - Lya emission(1216 A rest frame): Silva+12, Pullen+13, Croft+16
- H-alpha IM - Ha emission (6562 A rest frame): Gong+ 16; Silva+ 17
- HeII IM - HeII (1640 A): Visbal, Haimann, Byran 2015

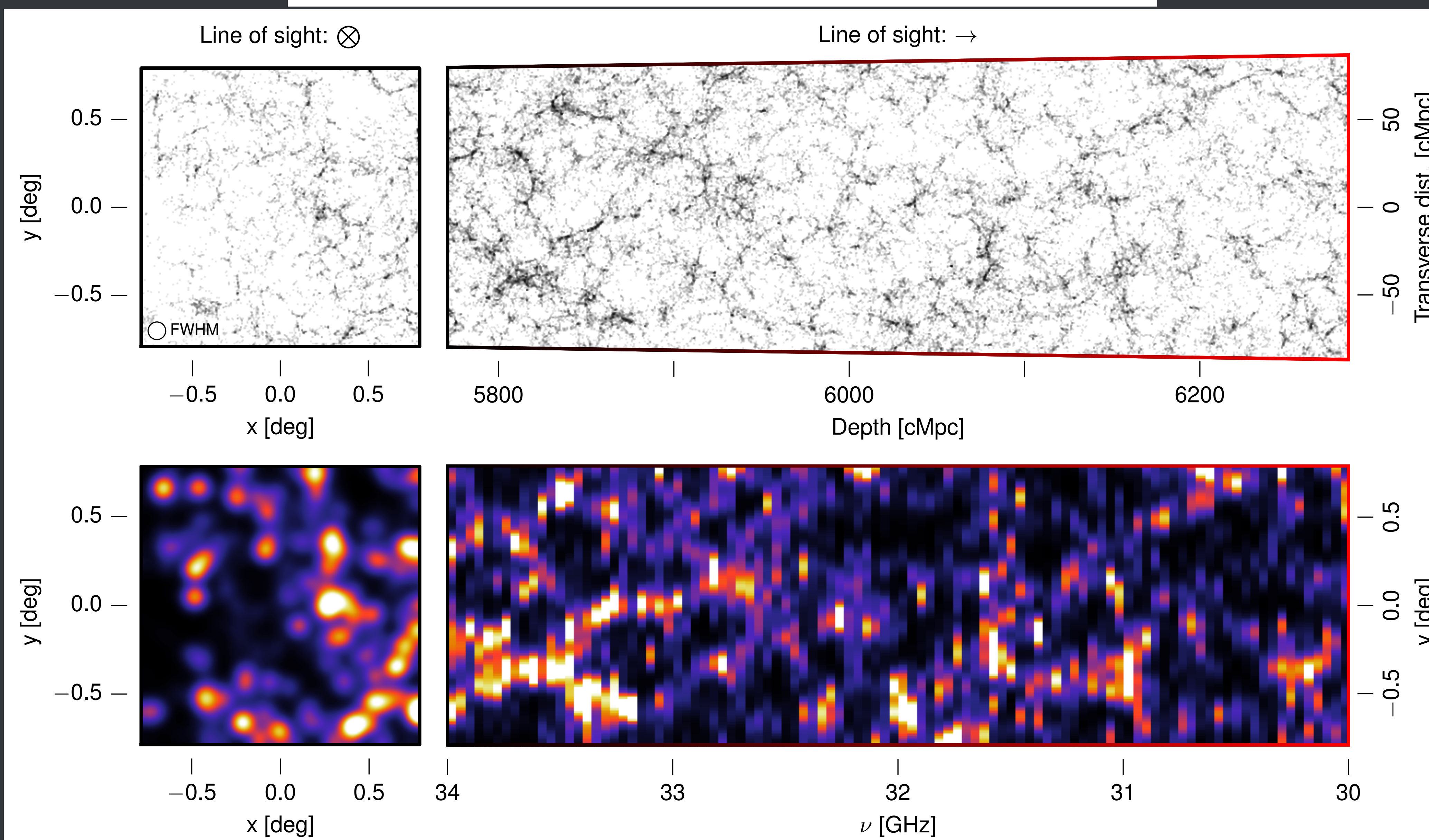
Intensity Mapping Sciences



A tracer of the 3D large-scale cosmic structures:

Luminosity-weighted density field

Li+16

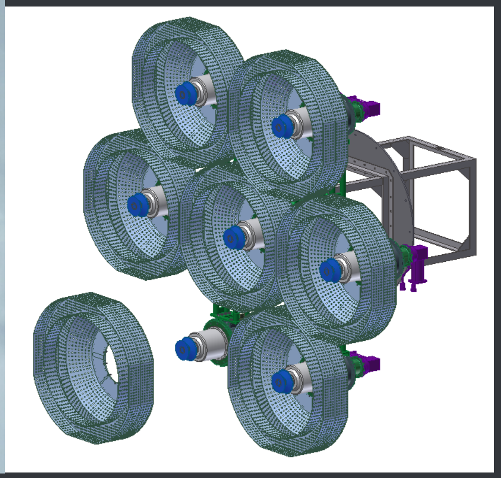


Astrophysics: L(M)

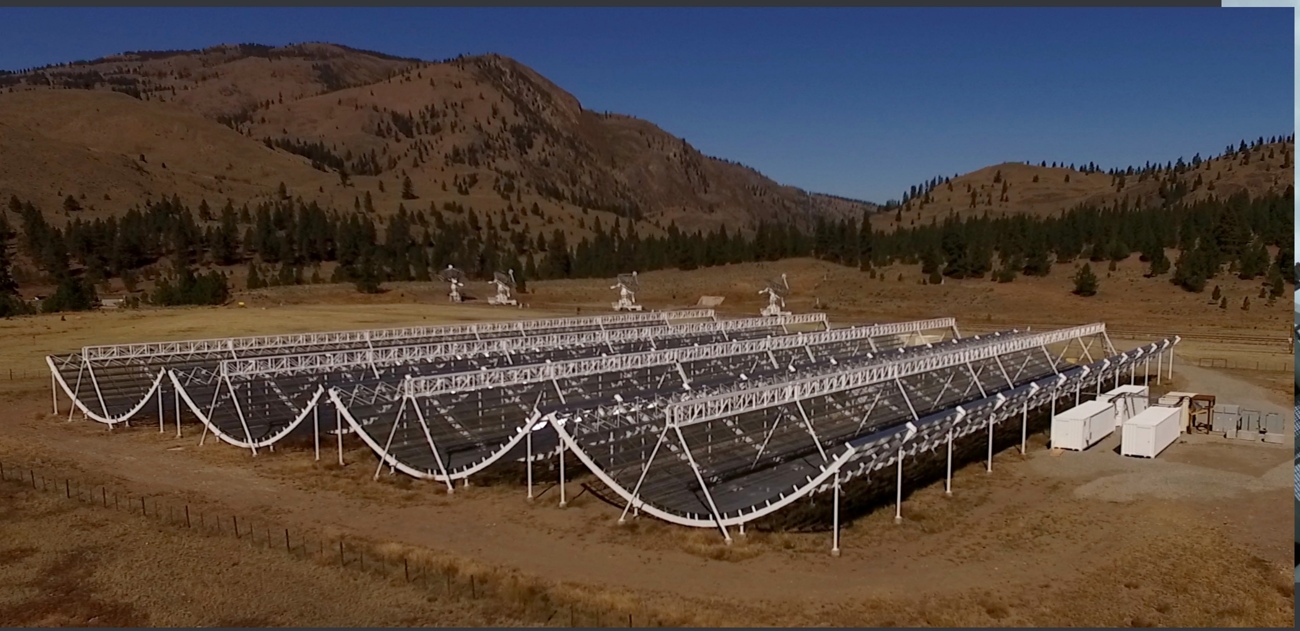
Cosmology: $P_L(k, z)$

Brightness temperature fluctuations $dT(\theta, \nu)$

21cm Intensity Mapping Experiments

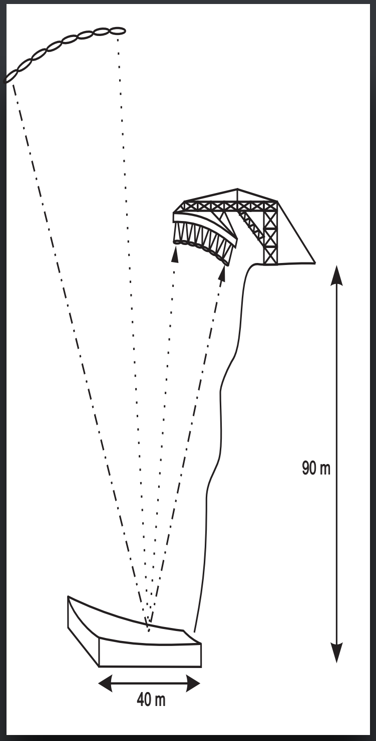


GBT-HIM multi-beam



CHIME

HIRAX



BINGO

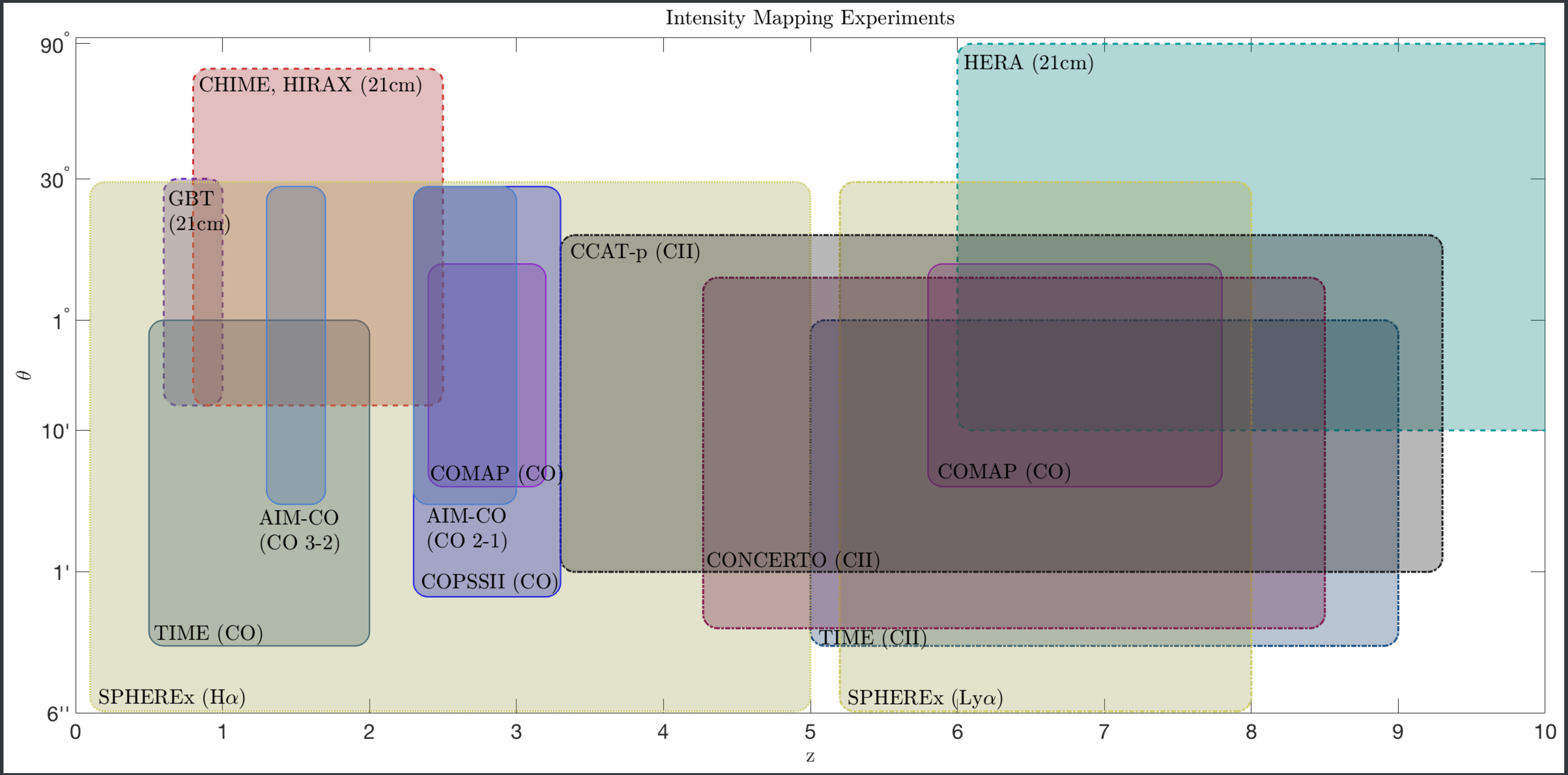
Tian-Lai/ CRT/BAORadio

Parkes IM

SKA-mid Telescope

(21cm, CO, [CII], Lya, Ha) Intensity Mapping Experiments

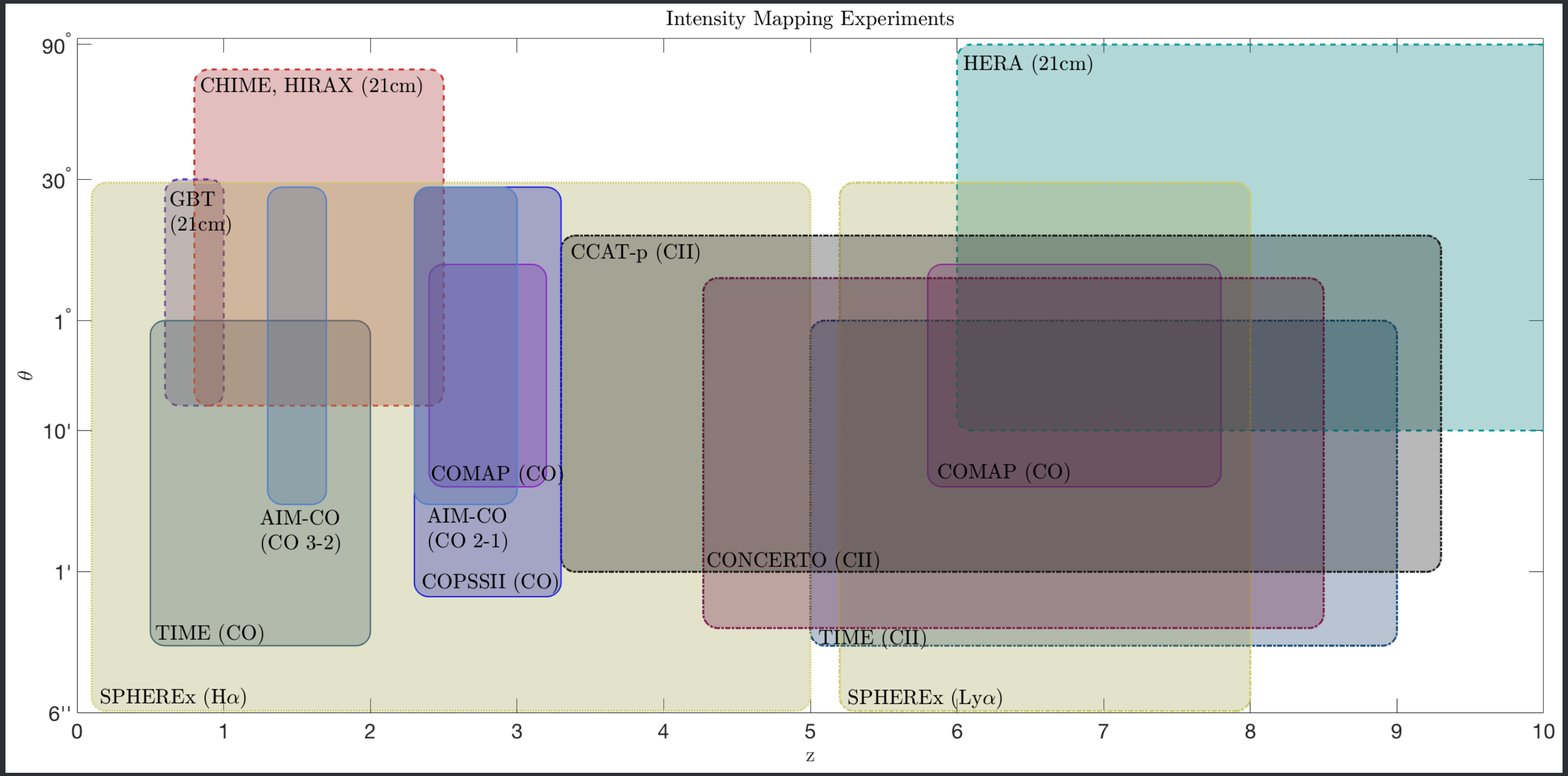
θ



z

Intensity Mapping status report (Kovetz+ in prep)

IM: a representative view of the Universe



Peak of Star formation

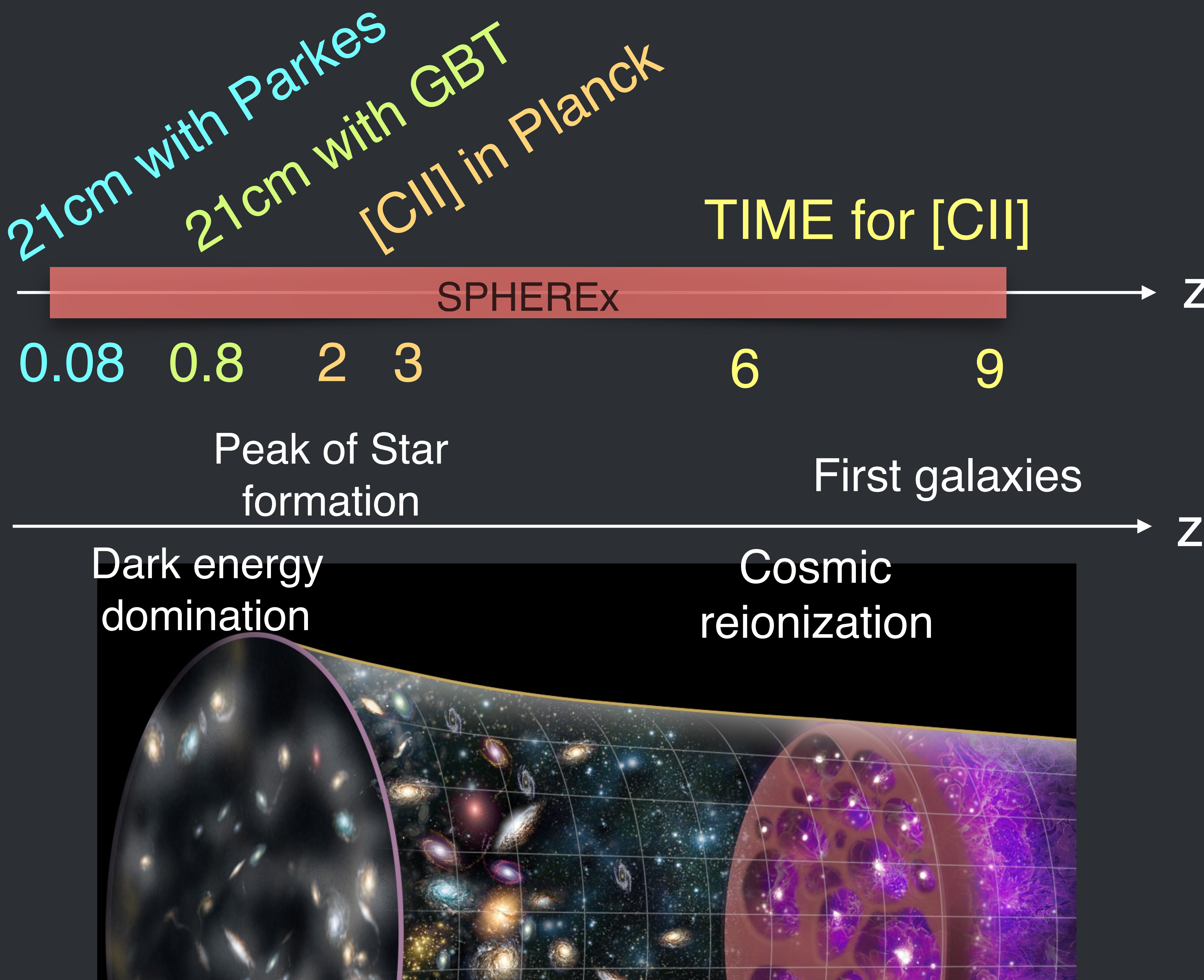
First galaxies

z

Dark energy domination

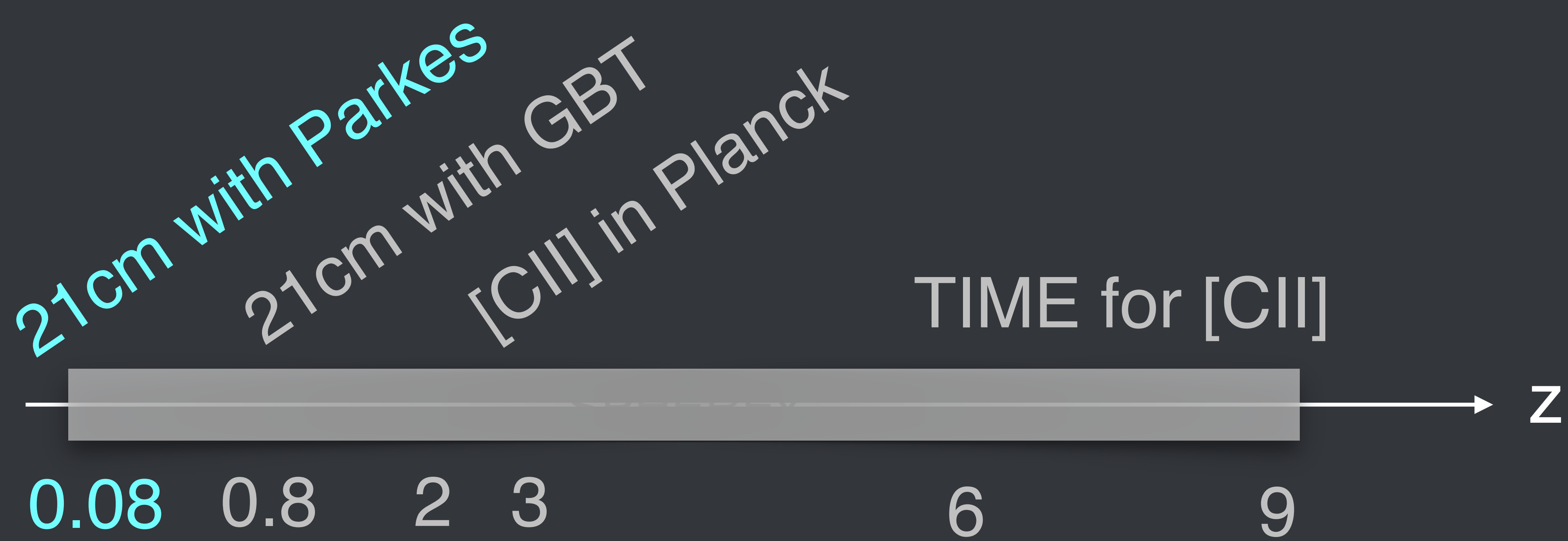
Cosmic reionization

Talk Outline



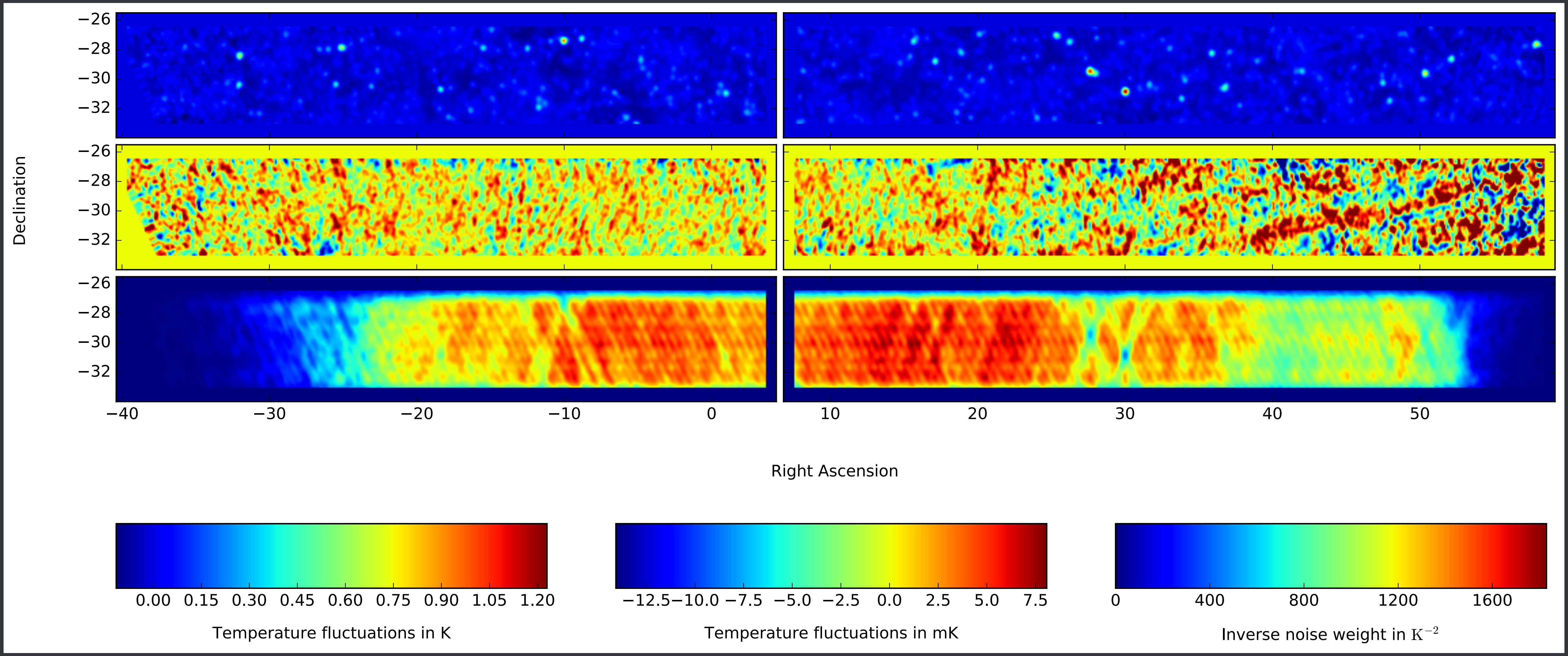
Large-scale Structure (LSS): Cross-correlation

21cm Intensity Maps at z~0.08 with Parkes Telescope



HI Intensity Maps from the Parkes Telescope

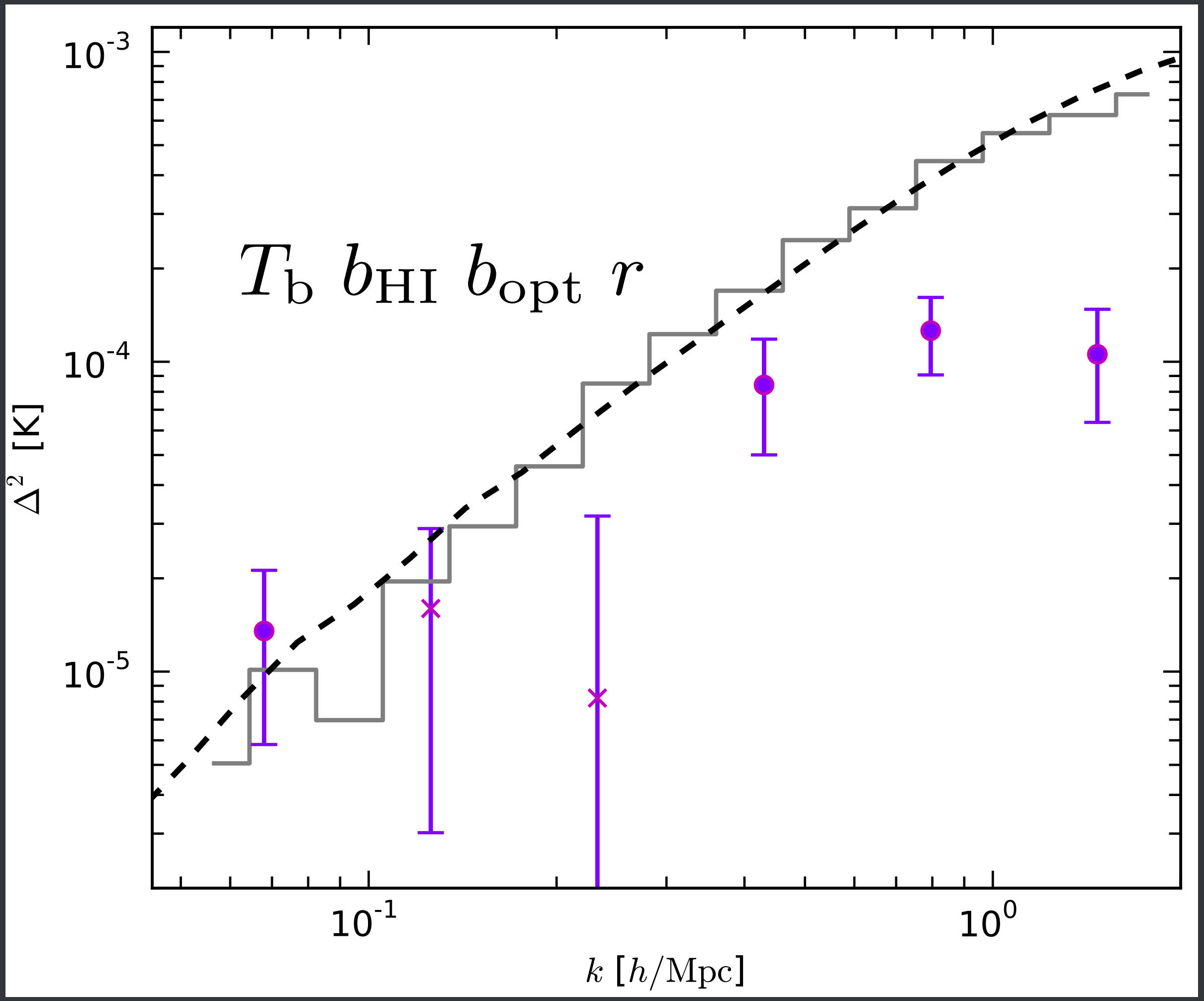
- Parkes L-band multi-beam observation, 0.06 < z < 0.1, over 1500 sq. deg. , 150 hrs



Anderson+17, arXiv:1710.00424

Parkes HI-2dF Cross-power spectrum

21cm x 2dF

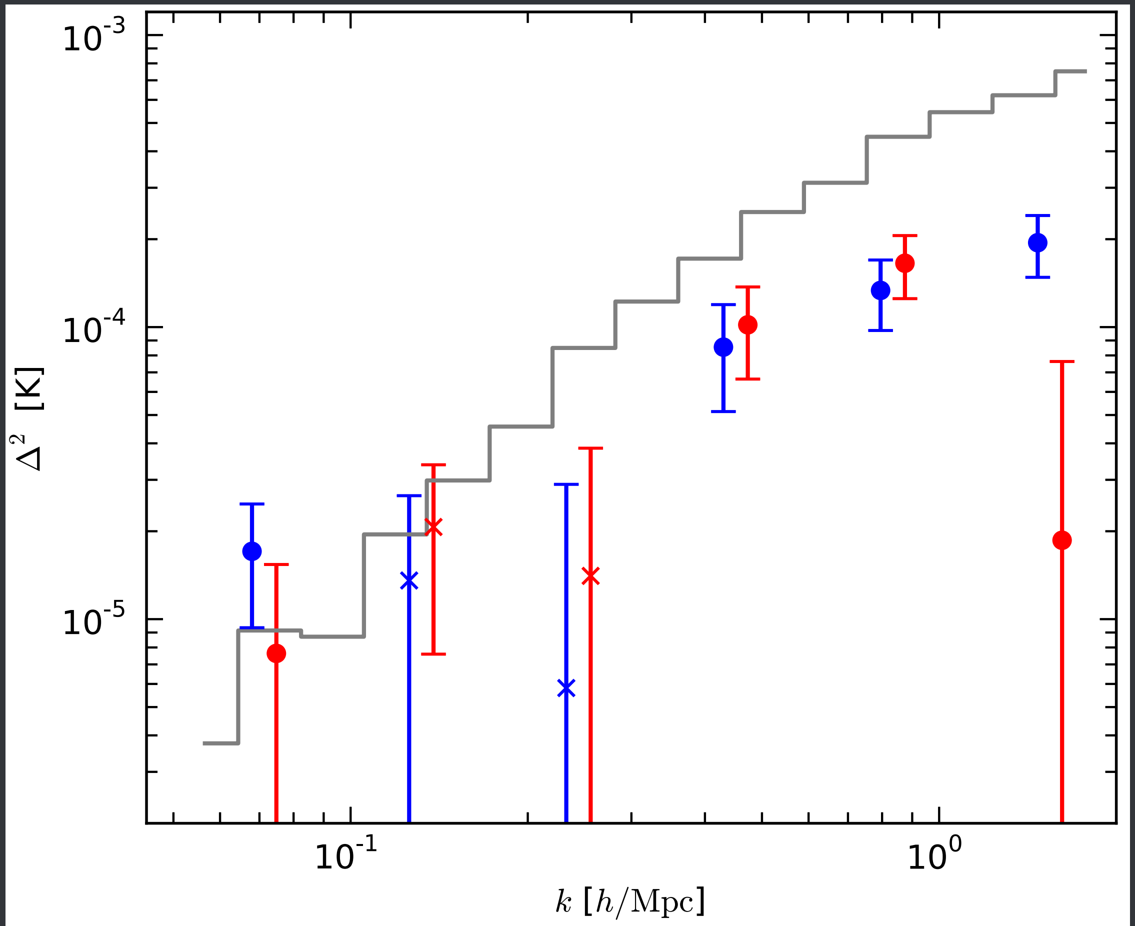


Anderson+17, arXiv:1710.00424

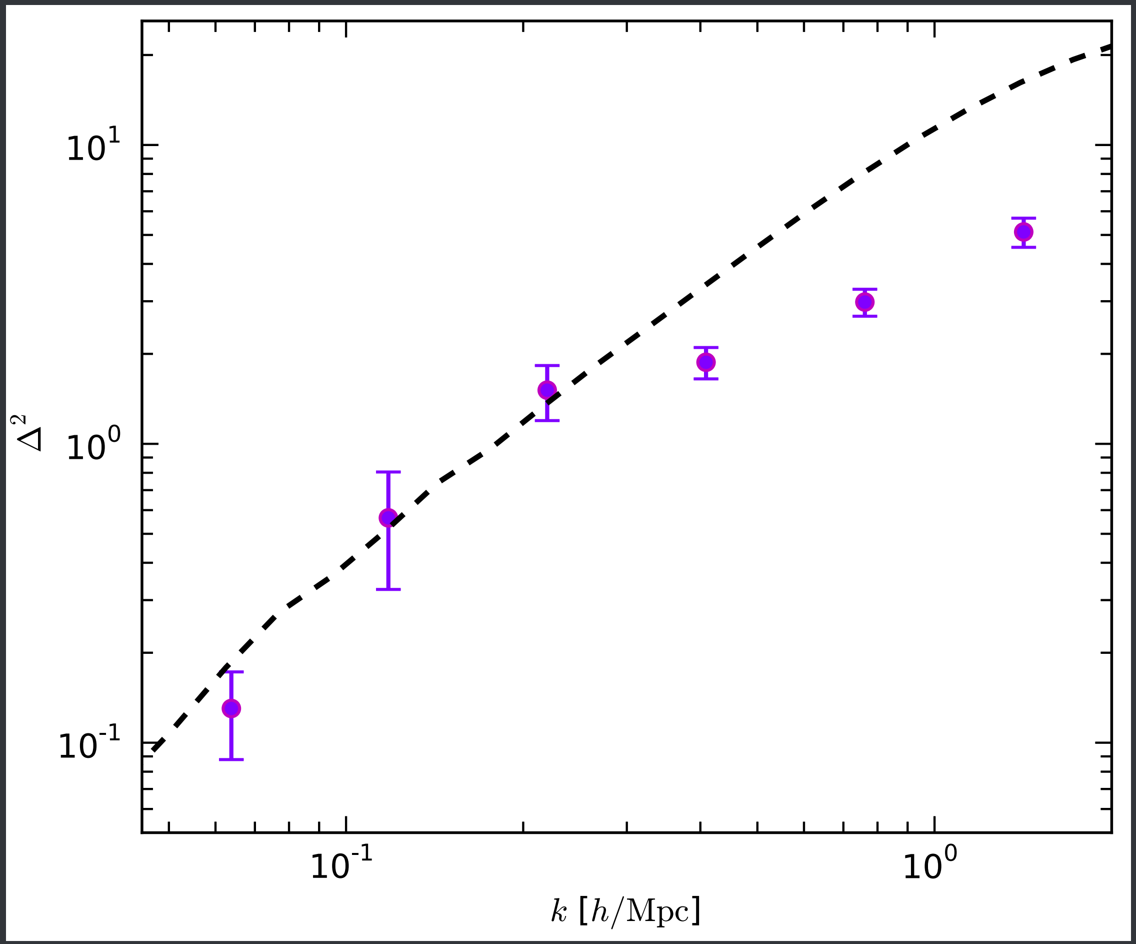
- Parkes L-band multi-beam observation, 0.06 < z < 0.1, over 1500 sq. deg. , 150 hrs
- Significant cross-power spectrum with 2dF galaxy measured at ~12 sigma.
- Comparison with individual detection HI surveys, HIPASS and ALFALFA.
  - Cross-power amplitude ~ $T_b\ b_{HI}\ b_{opt}\ r$
  - b_HI=0.85, Tb=0.064 mK (ALFALFA; Marin+ 2010), b_opt~1 (Cole+ 2005).
  - Cross-power shape: curves include linear + non-linear RSD effects.
  - r likely < 1. Power deficit at k~1.5 h/Mpc

Parkes HI-2dF Cross-power spectrum

21cm x (2dF blue, 2dF red)



2dF blue x 2dF red

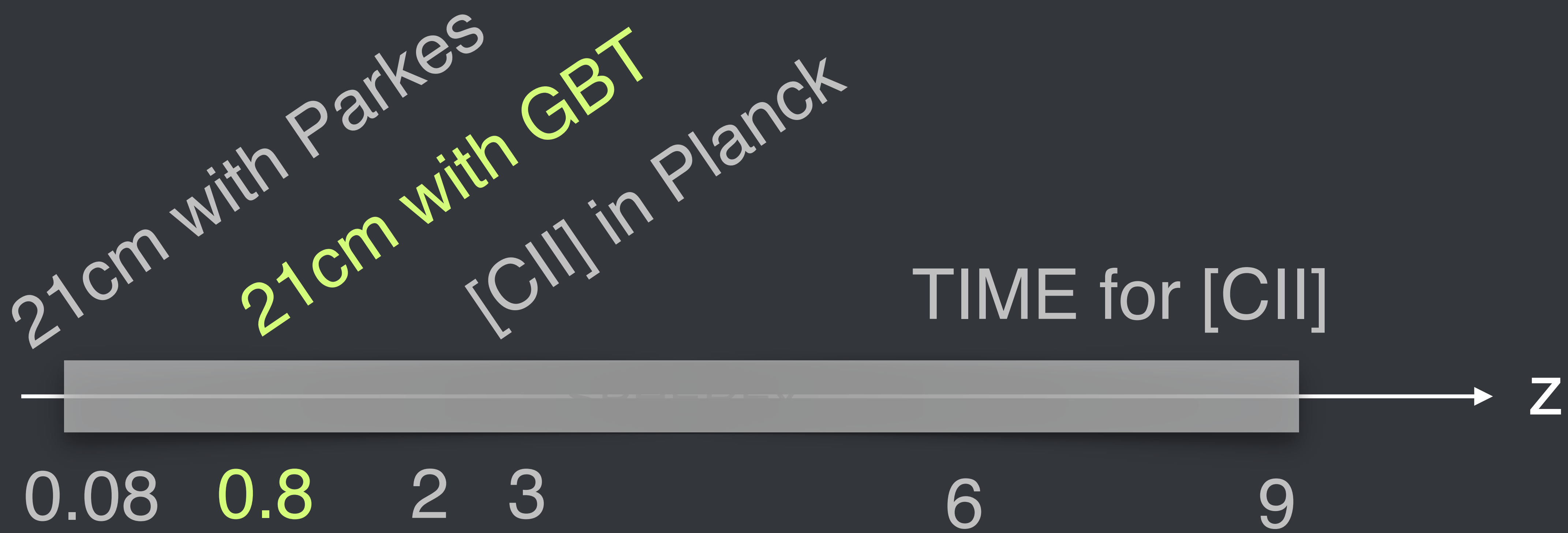


Anderson+17, arXiv:1710.00424

- Cross-correlating with 2dF blue and red galaxies separately.
- HI follows distribution of blue galaxies but does not trace red galaxies at k~1.5 h/Mpc
- HI-galaxy cross-correlation coefficient appears scale- and color-dependent.
- Neither simple HI halo model nor naive large-scale sims can capture this feature. We need better small-scale modeling!

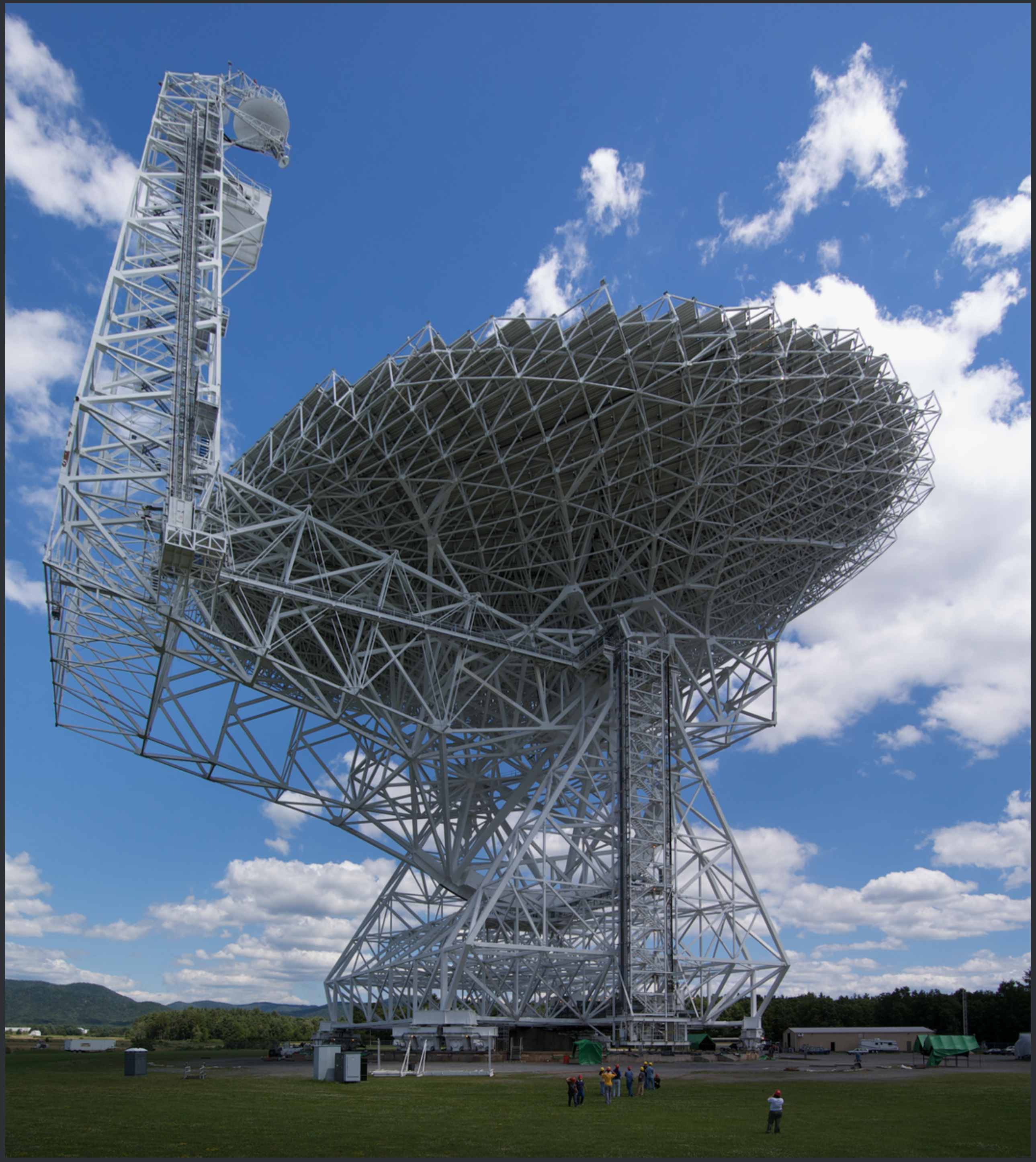
Large-scale Structure (LSS): Auto-power spectrum

21cm Intensity Maps at z~0.8 with Green Bank Telescope



21cm IM proof of concept

Pilot program at the Green Bank Telescope (GBT)

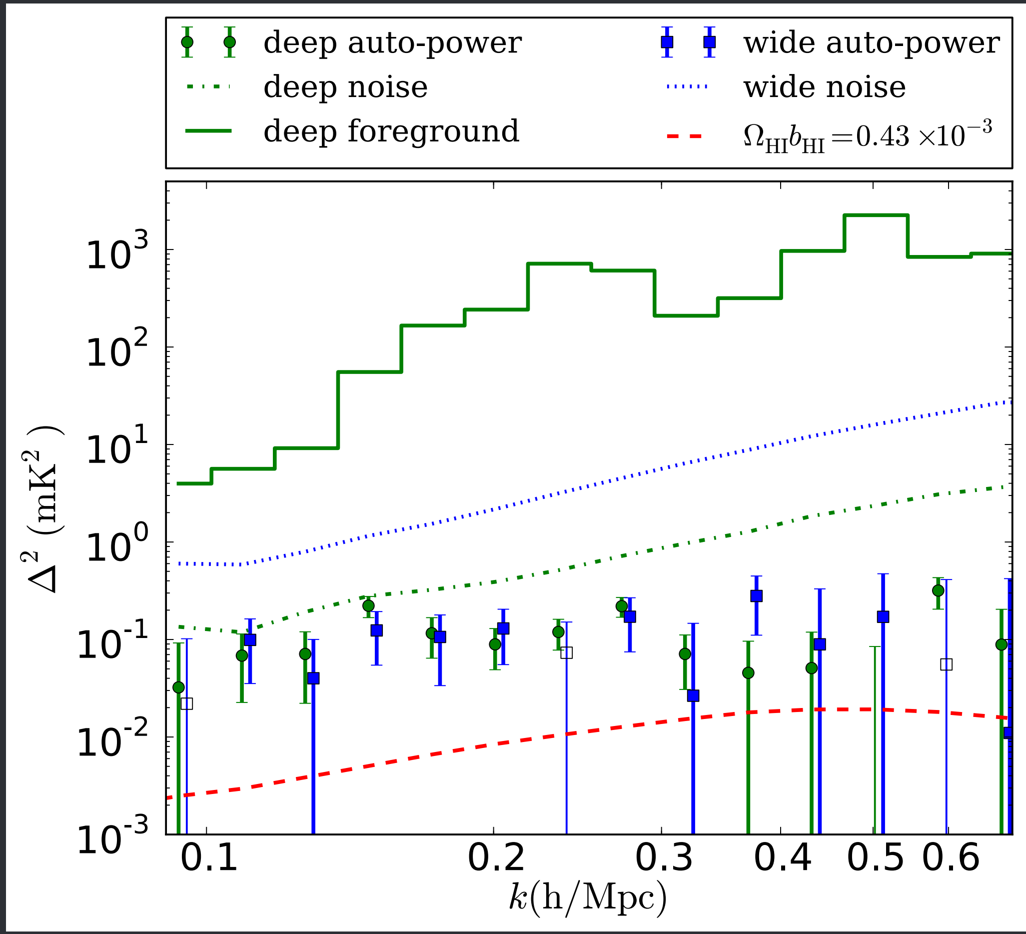


- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam ~ 15'
  - 9 h^{-1} Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc
- 100-m diameter. Large collecting areas
- Foregrounds are ~1000x stronger than the 21cm signals
- First detection in cross-correlation with DEEP2 galaxies at z=0.8 (Chang, Pen, Bandura, Peterson, 2010, Nature)

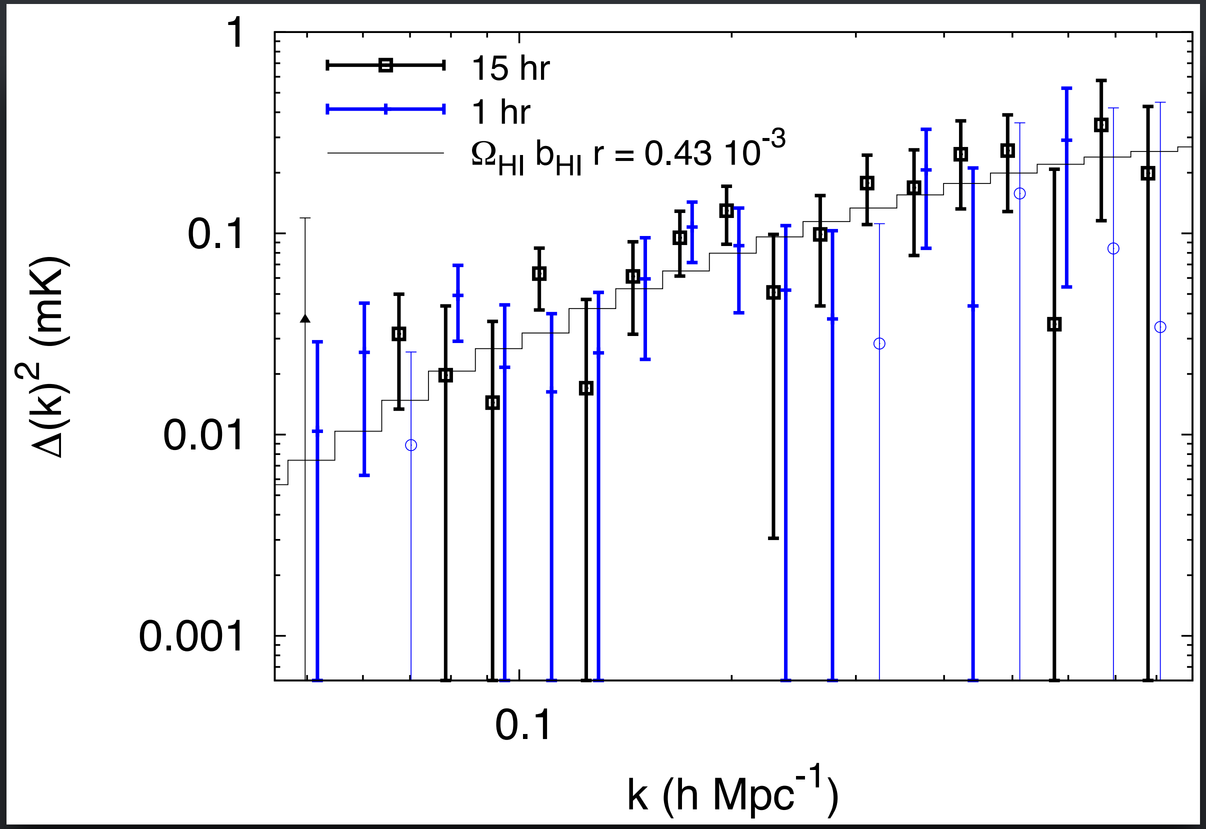
21cm Intensity Mapping at the GBT

- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam ~ 15'
  - 9 h^{-1} Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc

- 200-hr HI survey of the WiggleZ fields at $0.6 < z < 1$
- HI cross-power and auto-limits in 2013 at z=0.8 implies:
- $\Omega_{HI}\, b_{HI} = [0.62\ ^{+0.23}_{-0.15}] \times 10^{-3}$

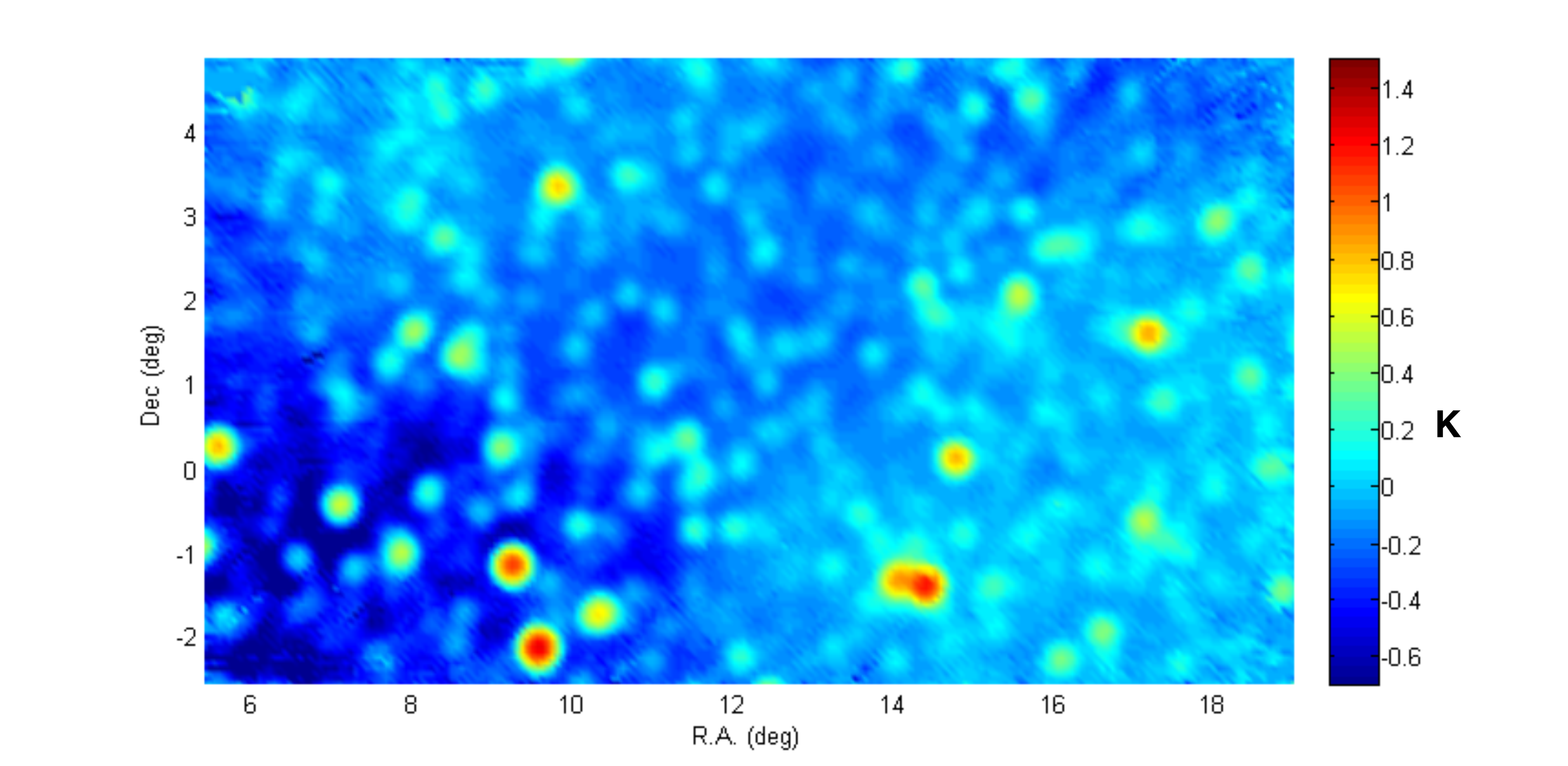


Auto-power limits, Switzer+13, GBT-HIM



Cross-power, Masui+ 13, GBT-HIM

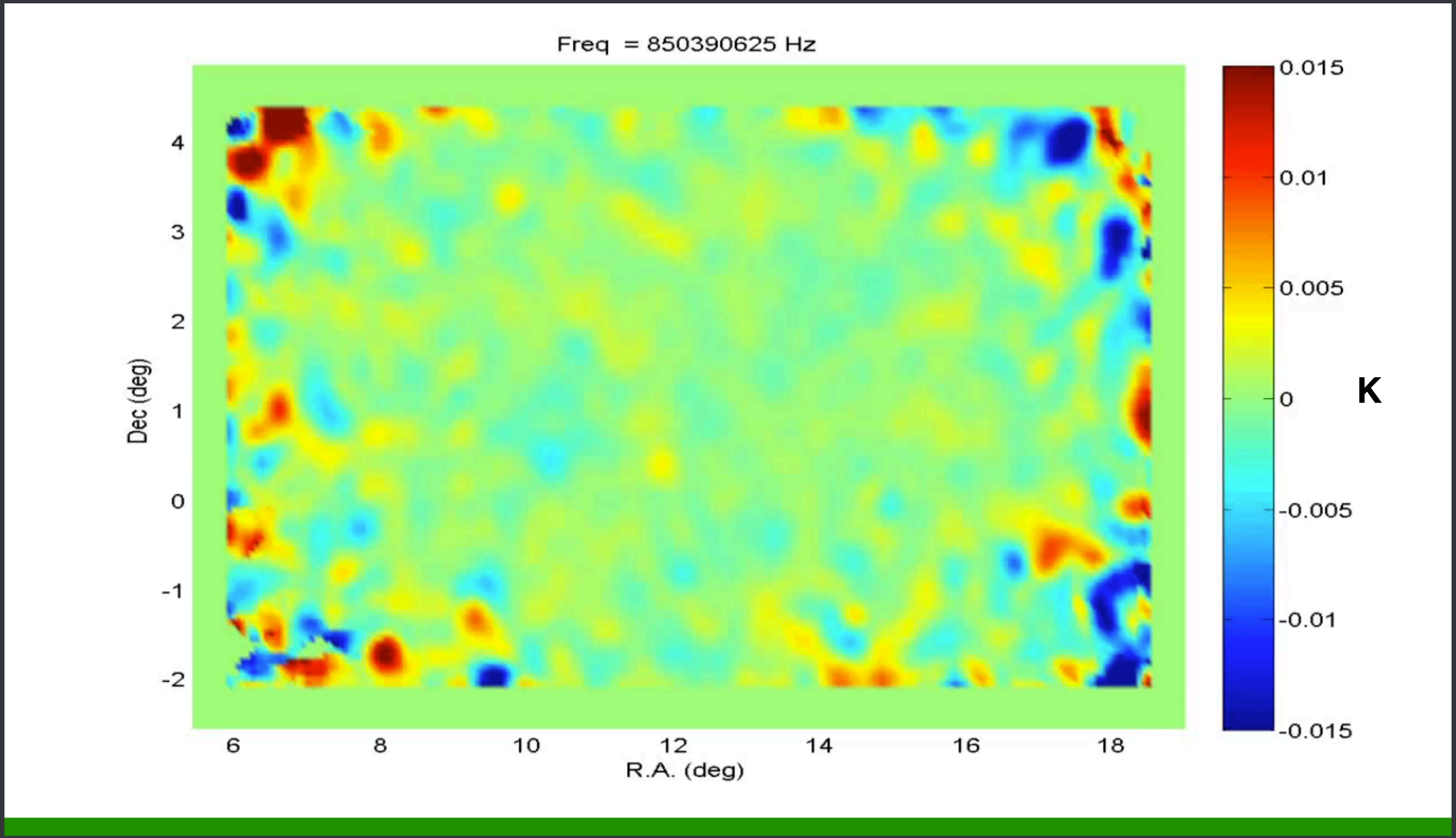
GBT-HIM Status Update



GBT WiggleZ 1hr field

- Analysis of ~800 hours of GBT observations 2010-2015.
  - WiggleZ 1hr, 11hr, 15hr, 22hr fields
- Improve HI power spectrum limits
- Measure HI-optical cross-power RSD effects
- Focus on the 1hr field, ~100 square deg, $0.6 < z < 1$:
  - Alternative Foreground cleaning techniques (Wolz + GBT-HIM team, 2016)
  - Polarization calibration improvement (Liao, Chang et al. 2016)
  - Polarization leakage power spectrum estimates (To, Chang et al., in prep)
  - Handling of residual ground-spill contamination (Liao, Chang, Masui et al., in prep)

GBT-HIM Status Update



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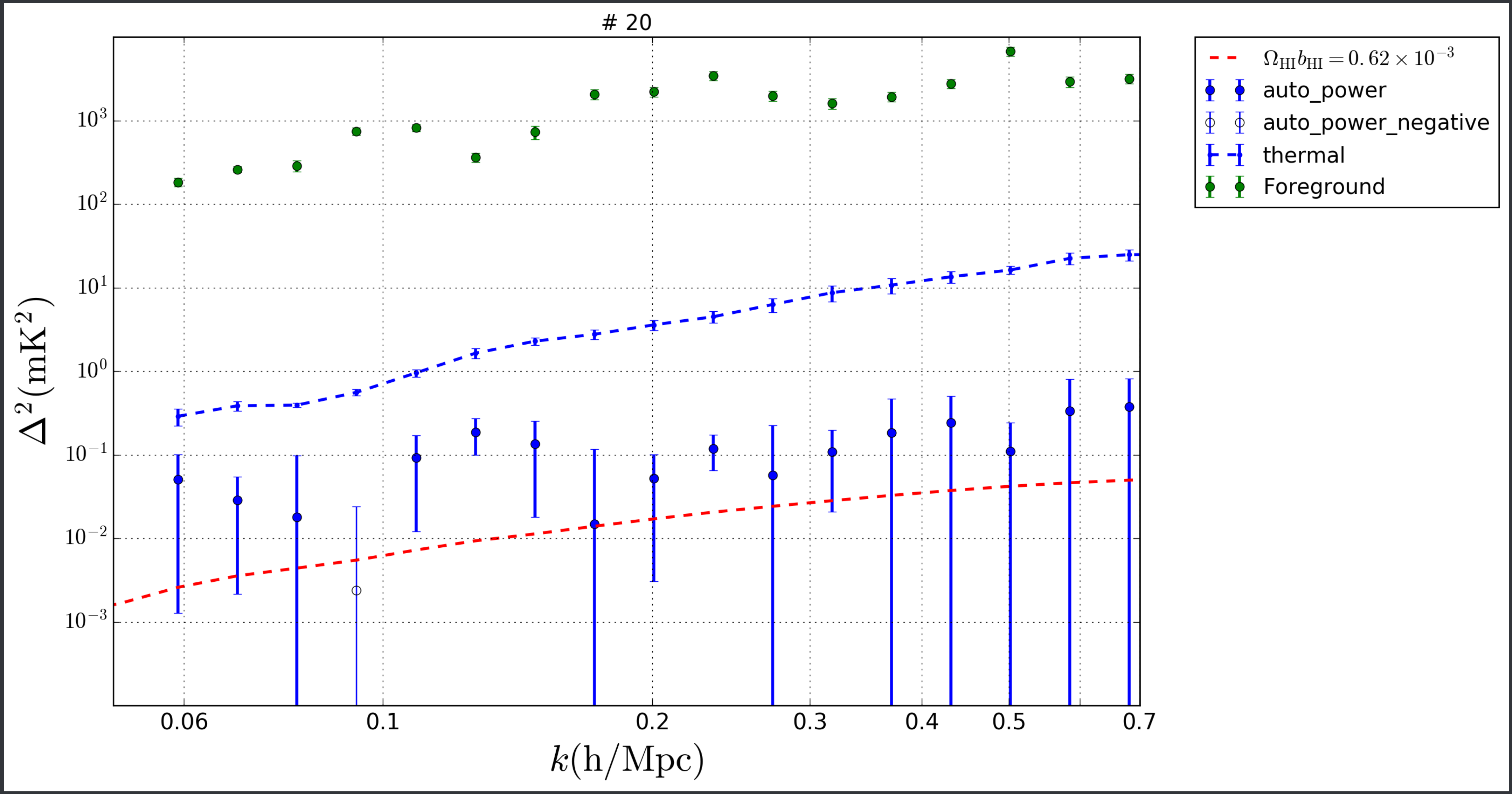
Work in progress:
Updated HI auto-power spectrum at z~0.8

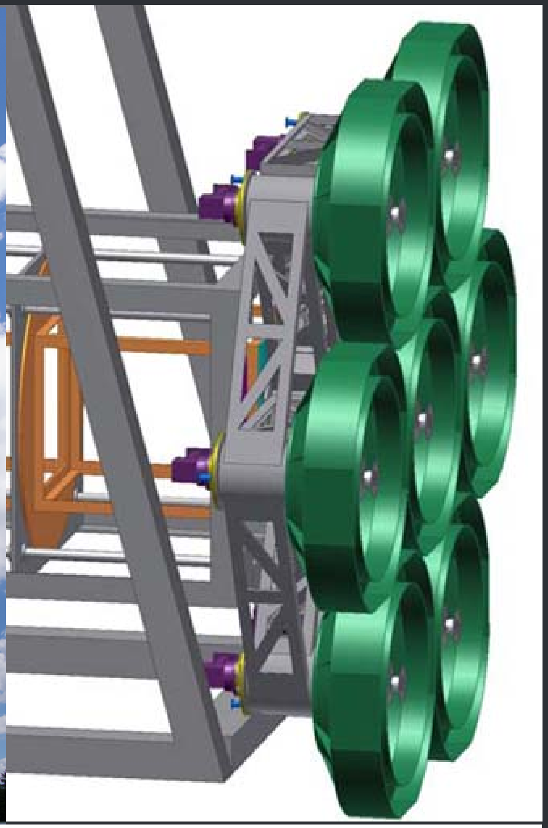


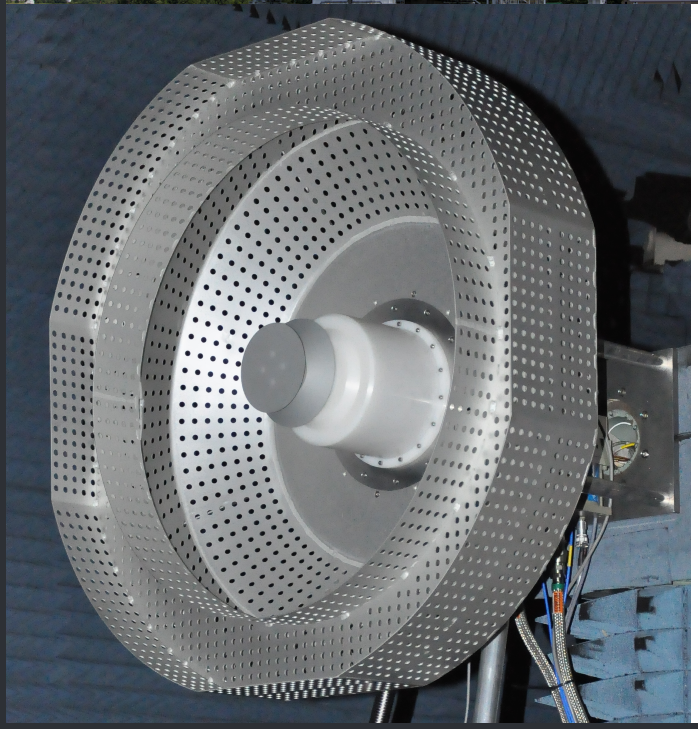
Chang, Liao, To + GBT-HIM, in prep.

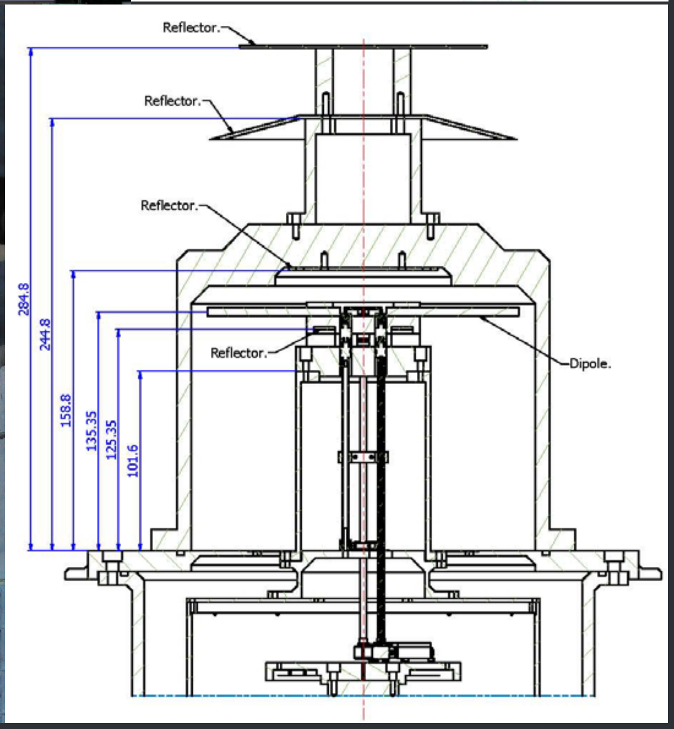
- Currently running jackknife tests and improving maps.
- Combining cross and auto-power for a better amplitude constraint

GBT-HIM

21cm Intensity Mapping for BAO & RSD studies





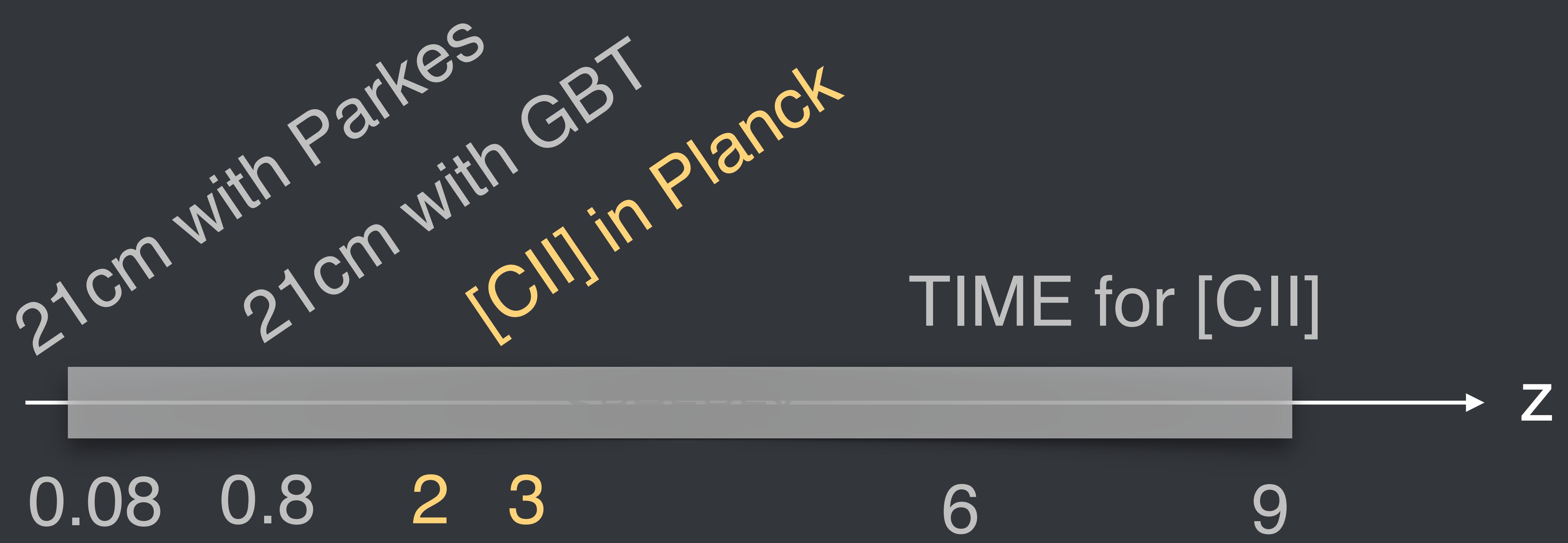


- GBT-HIM Project:
  - Building a 7-beam receiver at 700-900 MHz for redshifted HI survey at $0.6 < z < 1$ for BAO measurements.
- Use Short-backfire Antenna (SBA) with a edge-tapered reflector; with a cryogenic HDPE cover to reduce Tsys.
- Prototype tested on GBT in December 2014. Passed Design Review in October 2016.

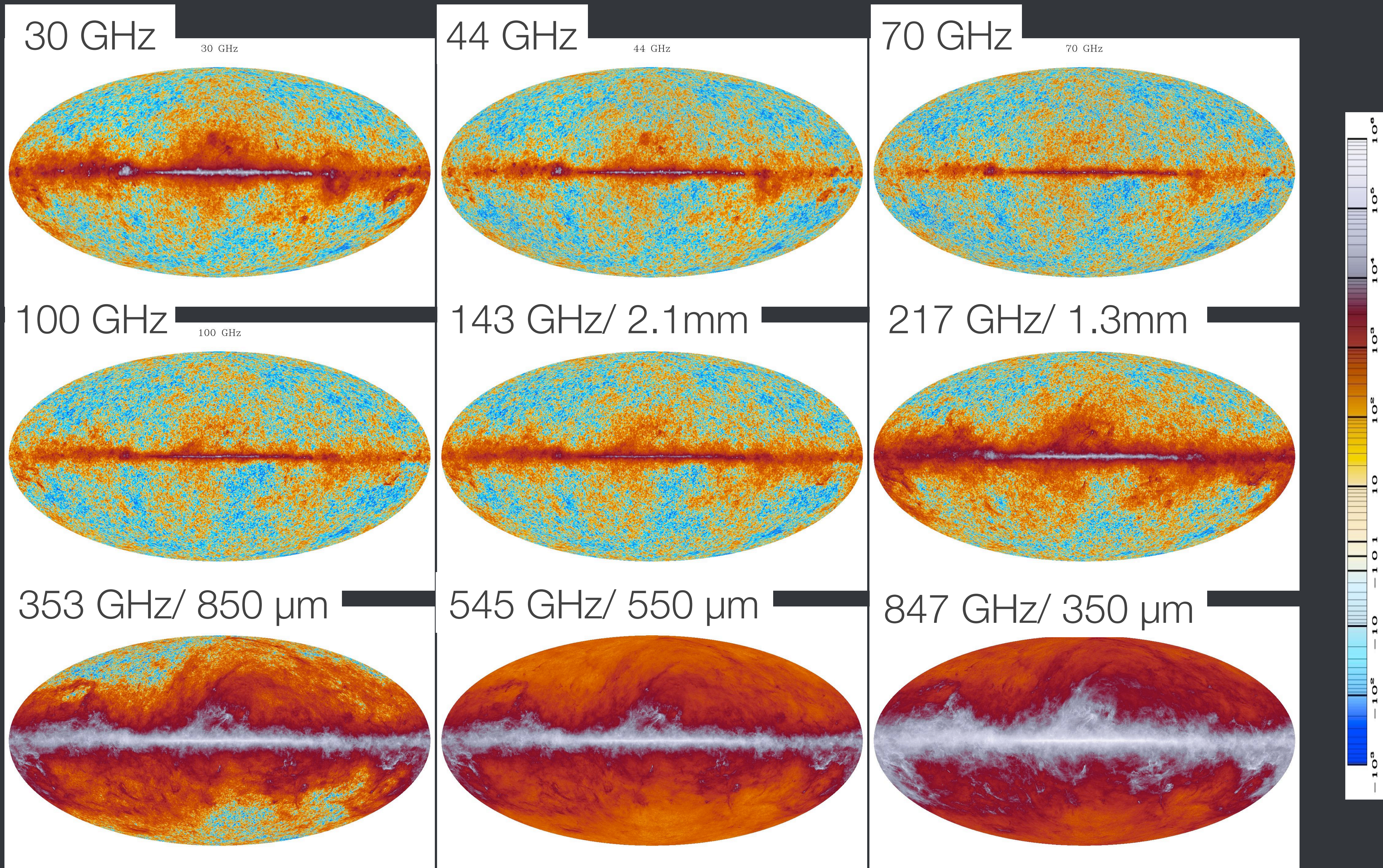
PI: T.-C. Chang

Large-scale Structure (LSS): Cross-correlation

[CII] Intensity Maps at z~2-3 with Planck and BOSS



Planck nine frequency maps



Planck Collaboration

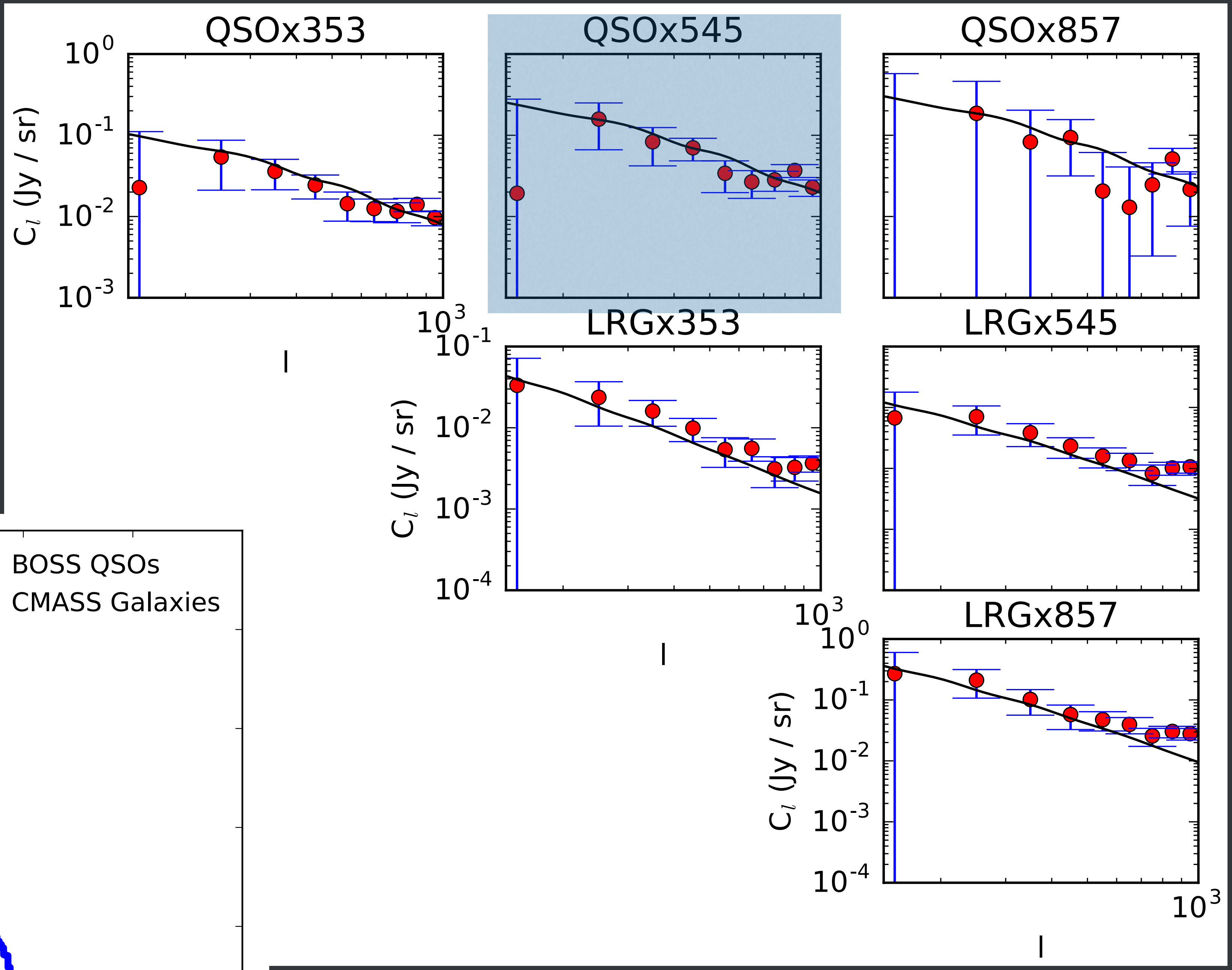
Planck x BOSS/CMASS

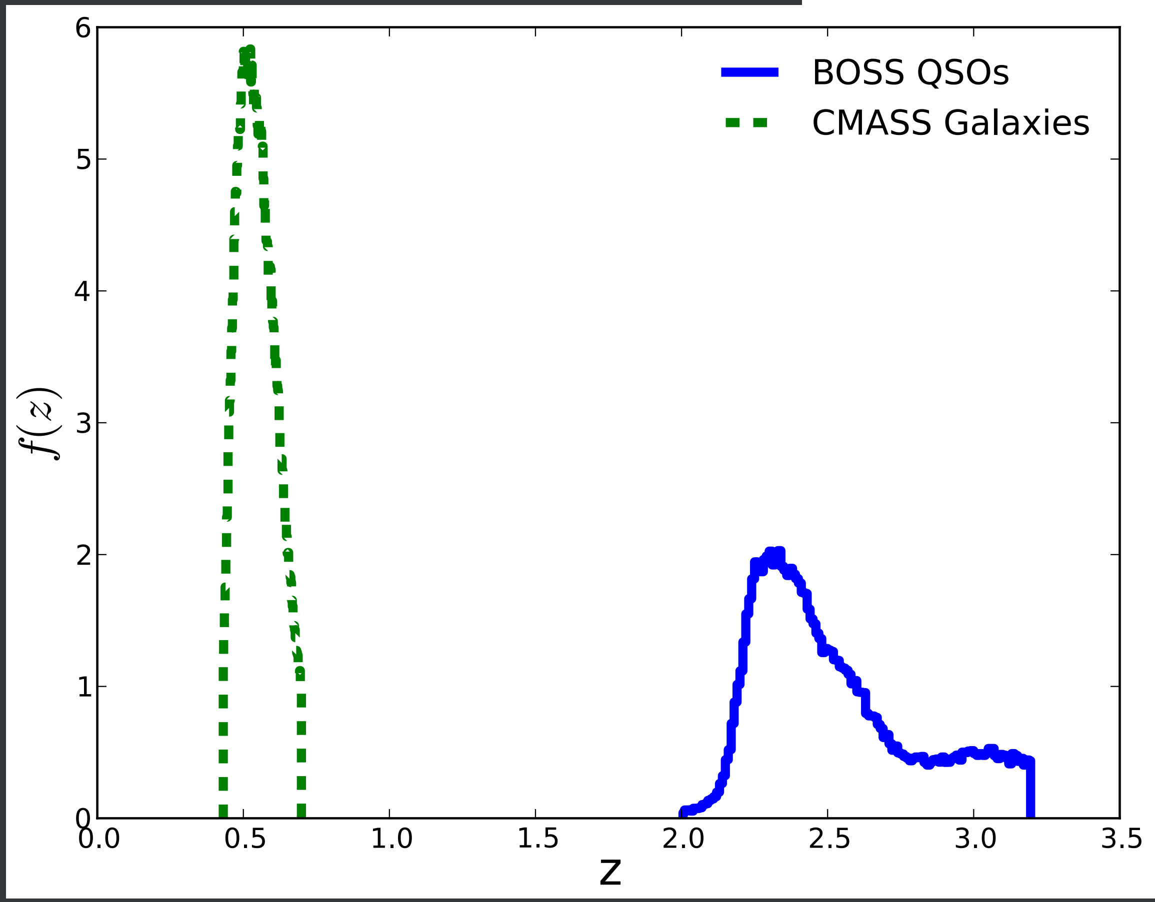
w/ Anthony Pullen, Olivier Doré, Shirley Ho, Paolo Serra

- [CII]: rest frame158 um =1.9 THz, brightest line in SFR galaxies
- Use Planck x BOSS to extract redshifted [CII] in Planck (projected along dz) associated with LSS traced by quasars
- [CII] tracers
  - Planck: 545 GHz → z(CII)~2-3
- LSS tracers
  - BOSS: CORE sample at z=2-3
  - CMASS: LRGs at z~0.5; null-test.
- Foregrounds
  - Galactic dust: 43% masked using Planck mask
  - CMB: subtracted using Planck 100 and143 GHz bands
  - CIB, tSZ, and [CII] jointly modeled in the cross-correlation with 353 and 857 GHz bands

Planck x BOSS/CMASS

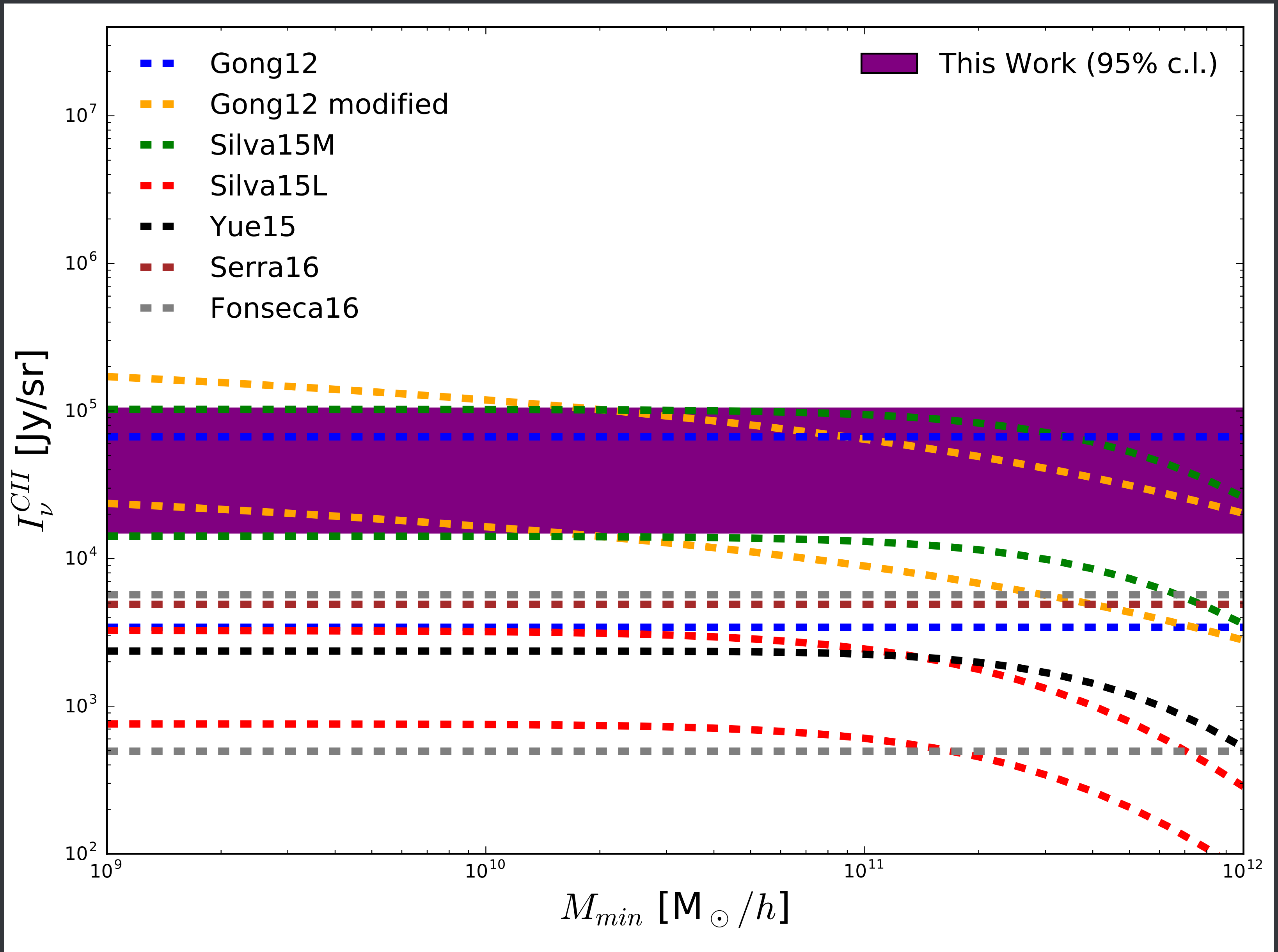
- Blue curve: best-fit model of CIB T_{dust}, z-dep., A(tSZ), A(CII)
- 100 < *l* < 1000, $0.02 < k_{perp} < 0.2$ [h/Mpc]





Pullen+ 2017, arXiv:1707.06172

Planck x BOSS/CMASS

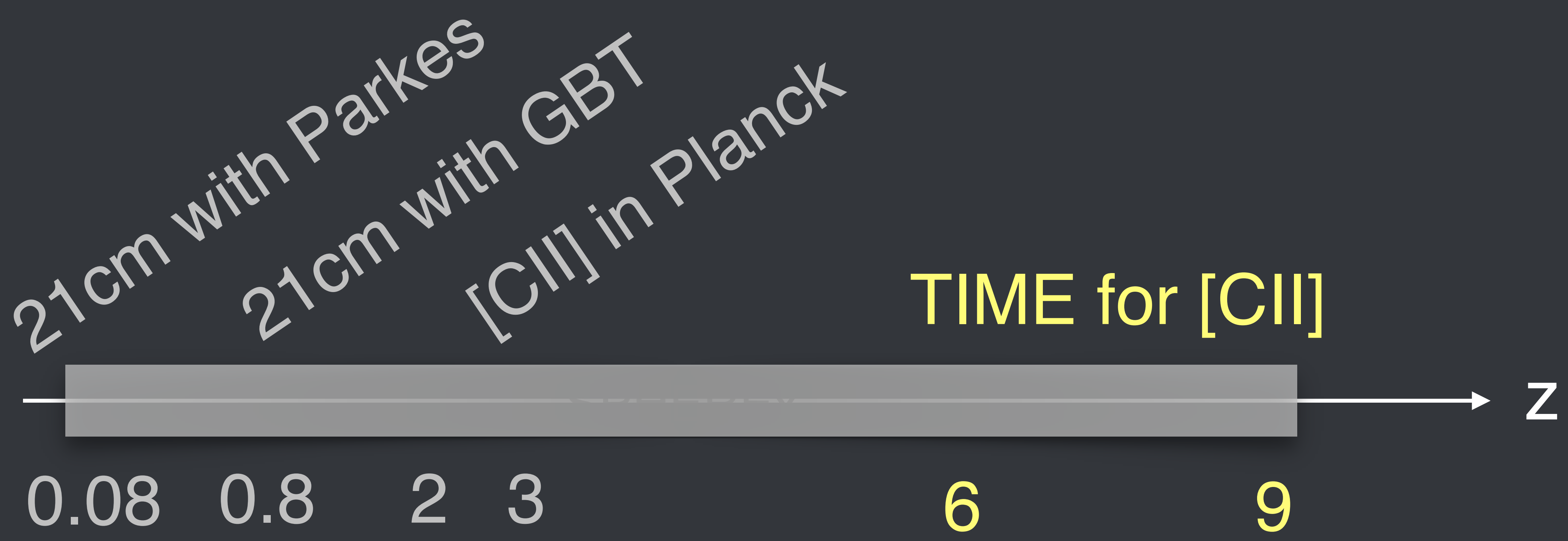


Pullen+ 2017, arXiv:1707.06172

- $I_{[CII]} = 5.5^{+4.8}_{-4.2}$ (95%) x 10^4 Jy/sr
- Constrain cosmic mean of [CII] at z=2-3; C+(z) abundance.

Cosmic Reionization (EoR):

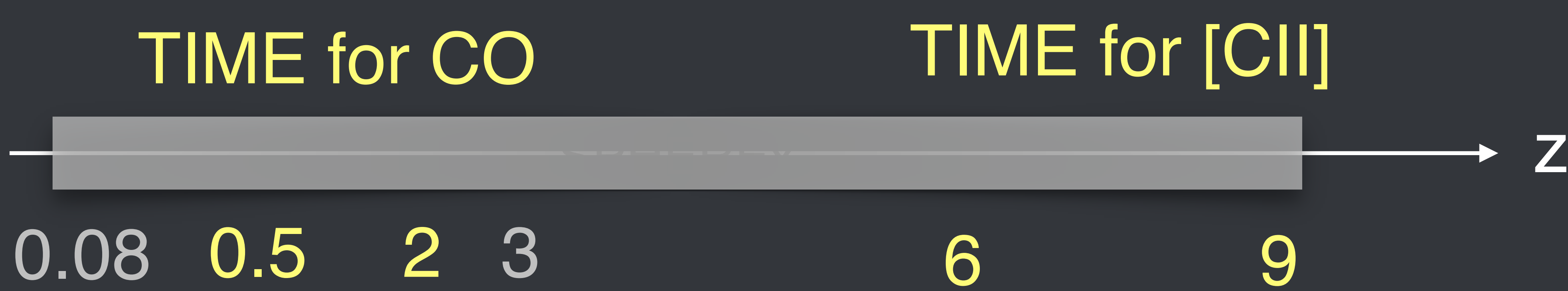
[CII] Intensity Maps at z~6-9 with TIME



Cosmic Reionization (EoR) & Cosmic Star Formation History:

[CII] Intensity mapping at z~6-9 & CO Intensity mapping at z=0.5-2

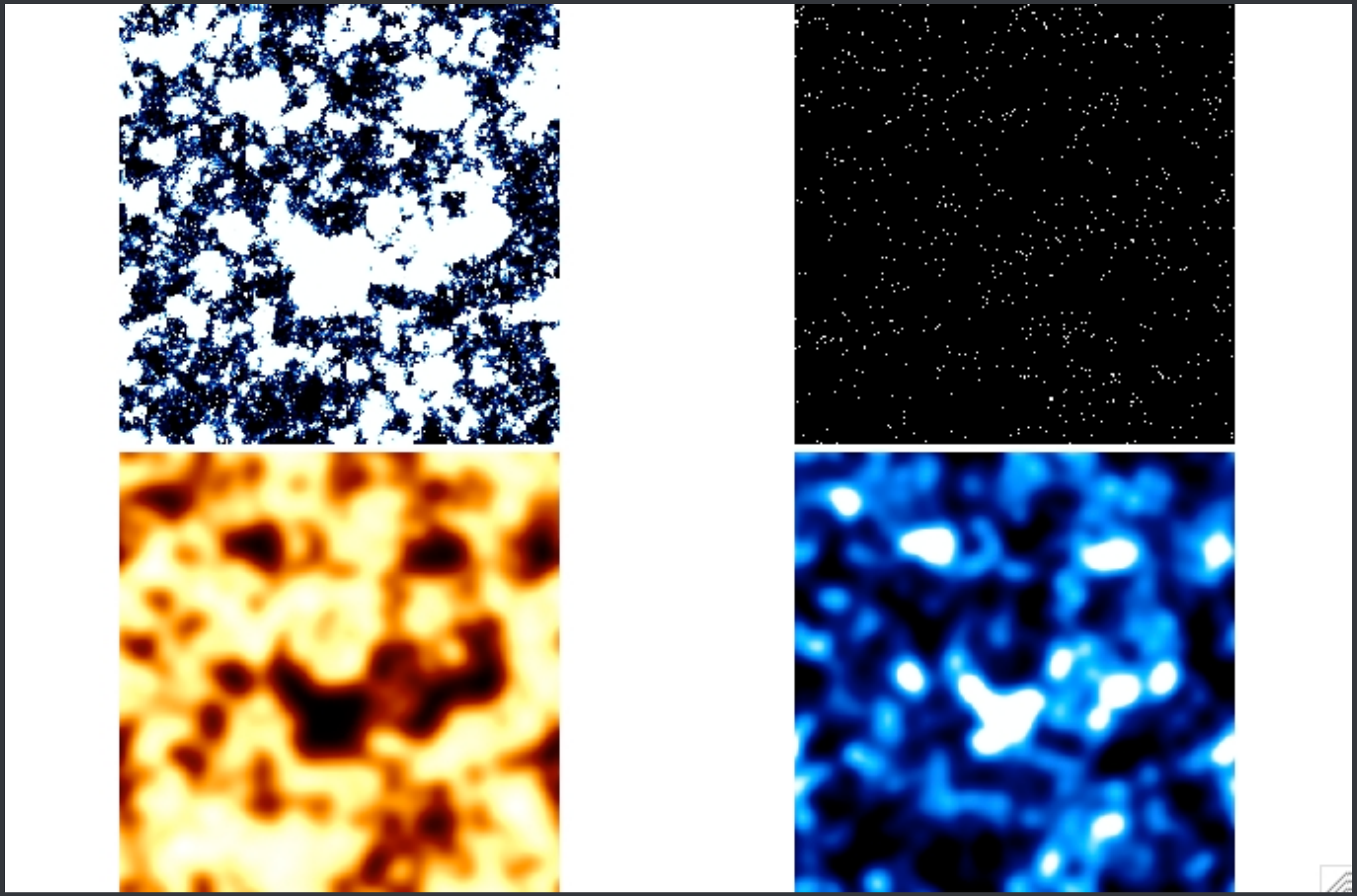
with TIME



CO/[CII]/Ha intensity mapping

Ionization field

galaxy/halo field



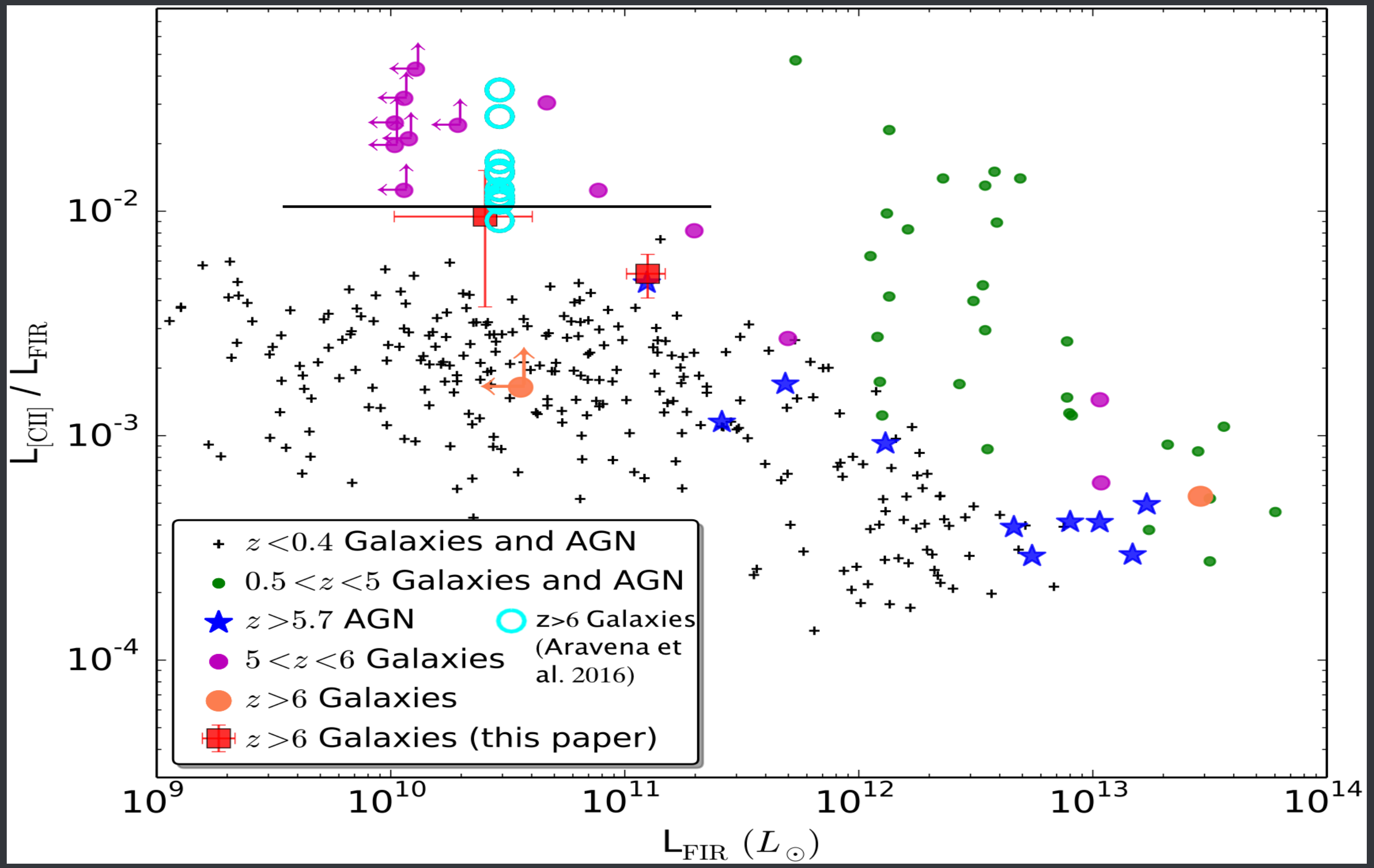
HI field

CO/[CII]/Ha field

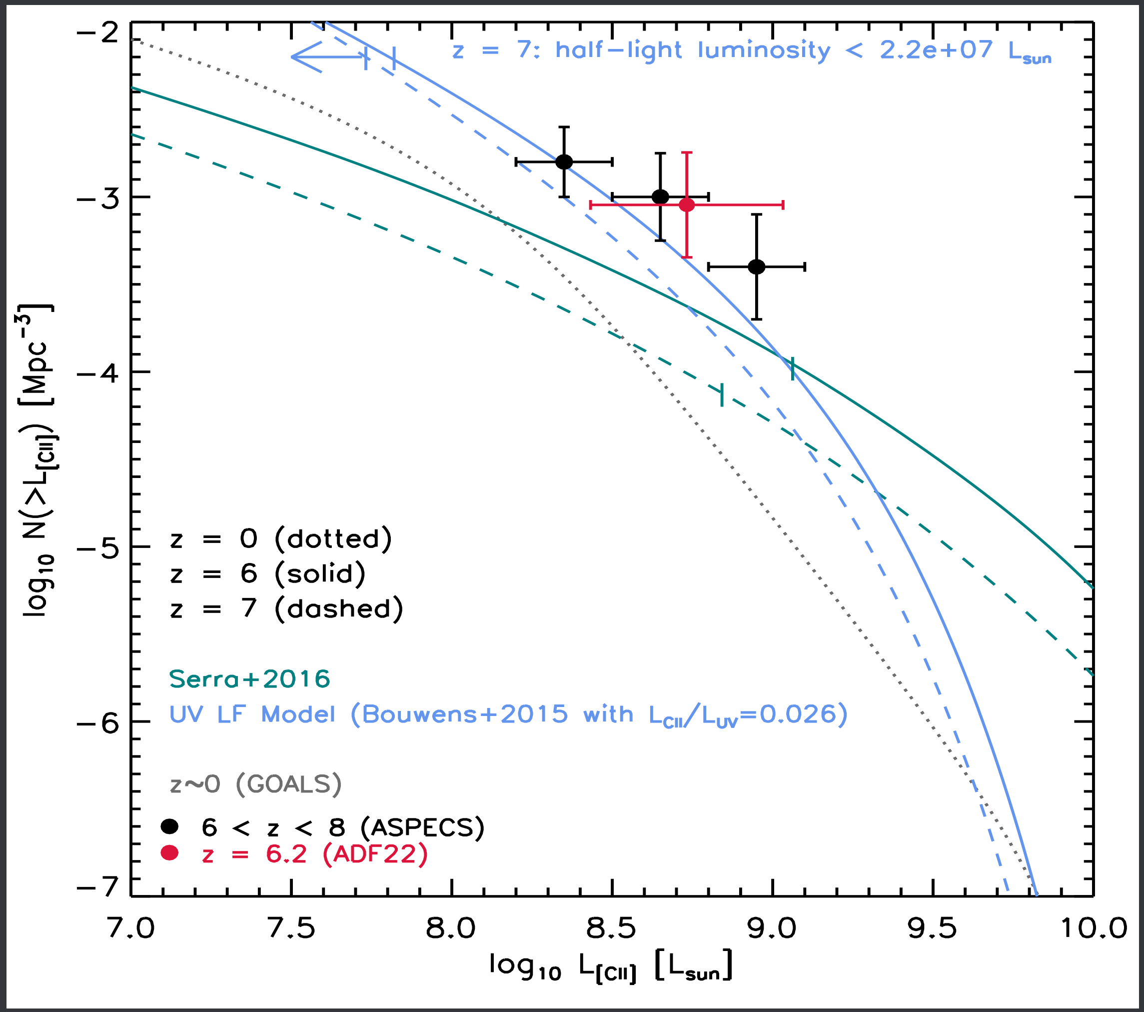
Lidz et al. 2011

- CO/[CII]/Ha trace star formation activities on large-scales at EoR, anti-correlate with 21cm emissions on ionized bubble scales and can be used to derive bubble evolution and reionization history (Lidz et al. 2009; Chang et al. 2015).
- Continuum foregrounds are much less of an issue. Need to worry about line interlopers.

[CII] at high-z



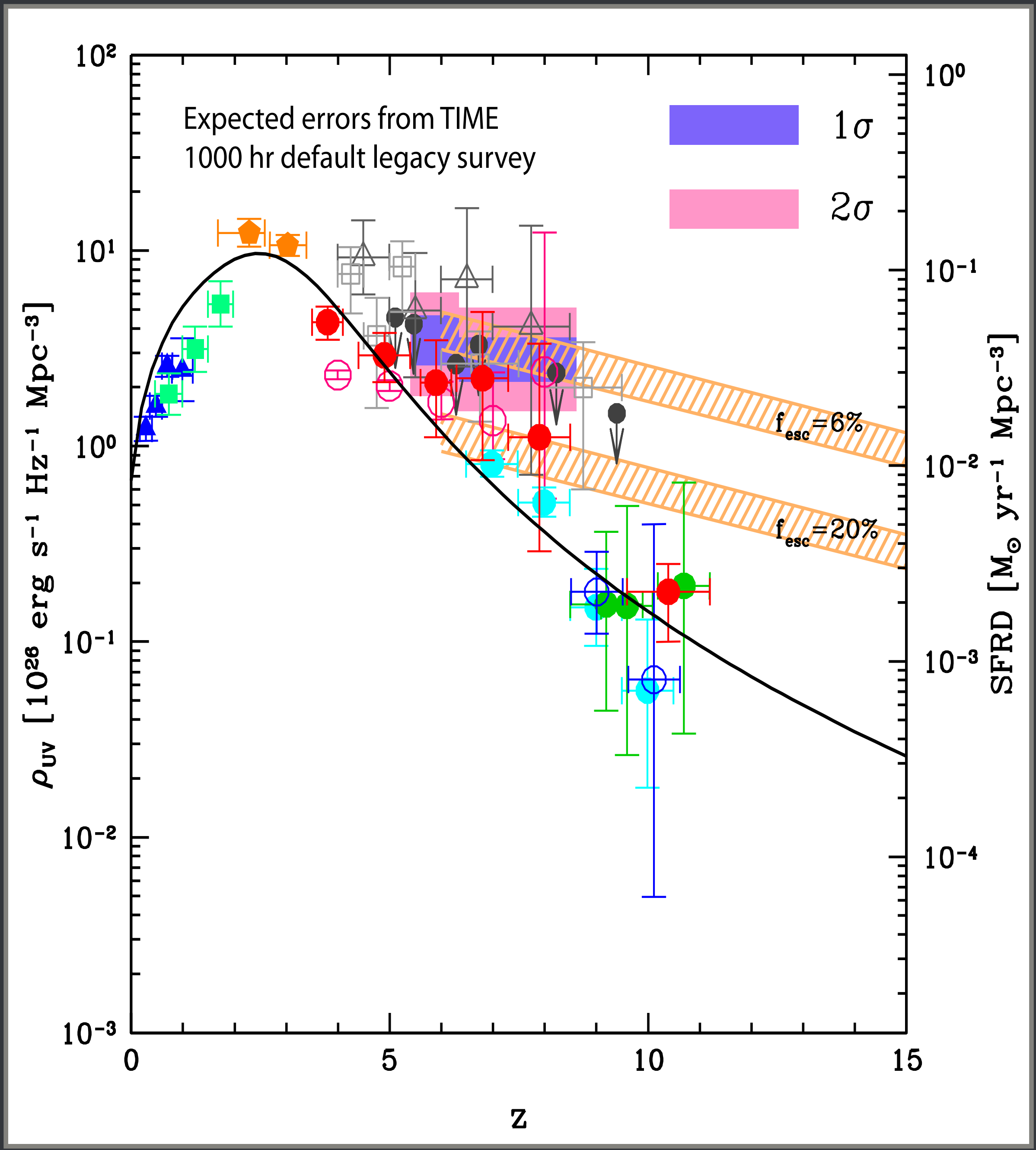
Willott et al. 2015



TIME collaboration

- [CII] is the major coolant in ISM, a tracer of Star formation activities.
- $L_{[CII]}/L_{FIR}$ appears to be > 0.01 at high-z from recent ALMA observations (Aravena et al. 2016, Capak et al. 2015)
- ALMA starts to constrain $10^{8.5\text{-}9}$ L_{sun} systems (Aravena et al. 2016, Hayatsu+17)

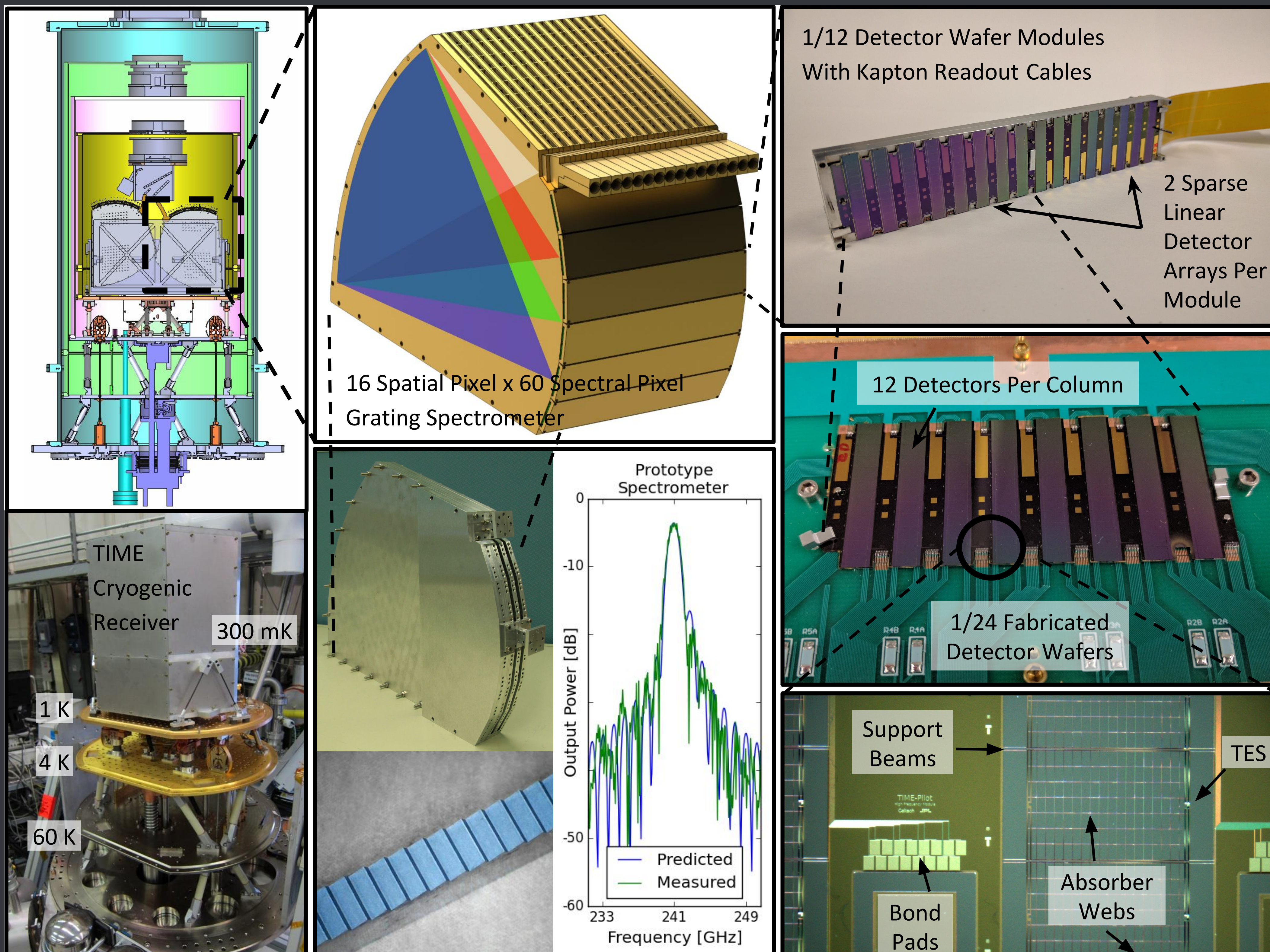
TIME: [CII] Intensity Mapper
Tomographic Ionized-C Mapping Experiment



TIME collaboration

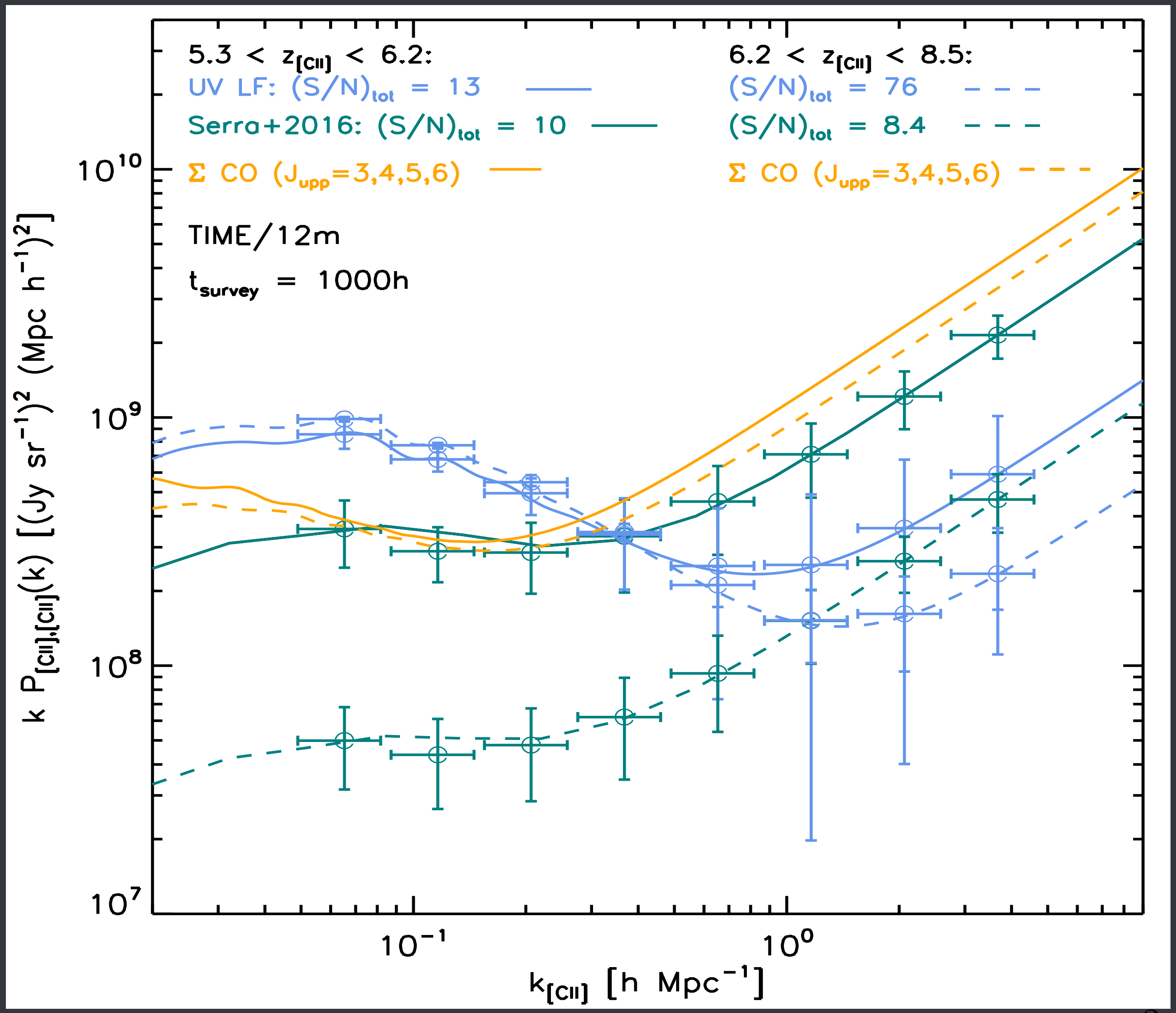
- A [CII] Intensity Mapper for EoR at 6<z<9
    - 1840 TES bolometer array
    - 195-295 GHz, 32-channel spectrometer
    - to be installed on APA 12-m.
    - Caltech (J. Bock), JPL (M. Bradford, T.-C. Chang), ASIAA (C.-T. Li), UCI (A. Cooray), U Arizona (D. Marrone)
    - Engineering run expected winter 2018.
- [CII] IM traces star formation activities
- 1000 hours of observation, starting ~2019

TIME Instrument



TIME collaboration

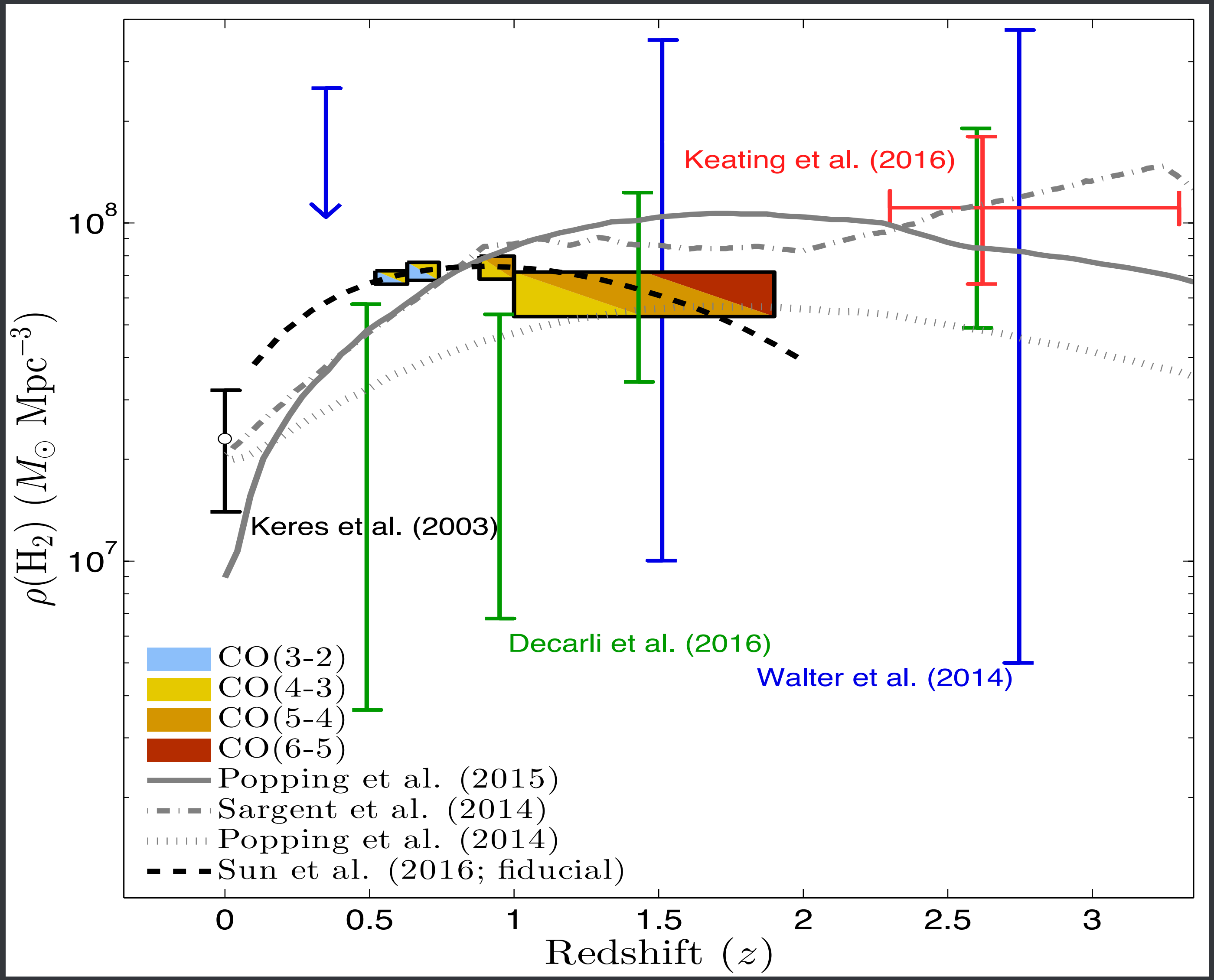
TIME measures [CII] Power Spectra at z~6-9



TIME collaboration

- [CII] intensity mapping constrains the integral of luminosity function via clustering and shot-noise power spectrum
- TIME measures [CII] clustering on large-scales, the luminosity-weighted bias and mean [CII] amplitude at $5.5 < z < 8.5$ at high significance (model dependent).

TIME measures CO/H_2 abundance at z=0.5-2

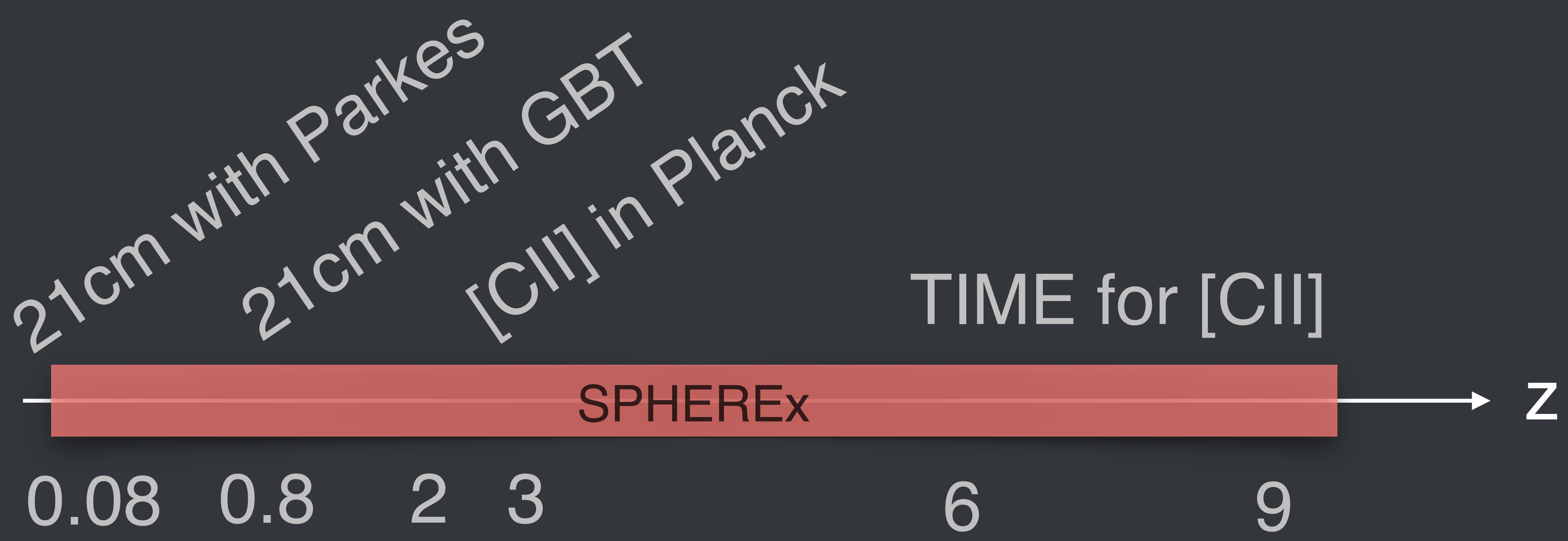


TIME collaboration

- TIME will measure multiple CO J rotational transitions at 0.5 < z < 2
- Can be achieved via in-band cross-correlations of different J lines
- TIME will constrain the cosmic molecular hydrogen abundance across redshifts

LSS and EoR Sciences:

Lya, Ha Intensity Maps at z~0-10 with SPHEREx



SPHEREx

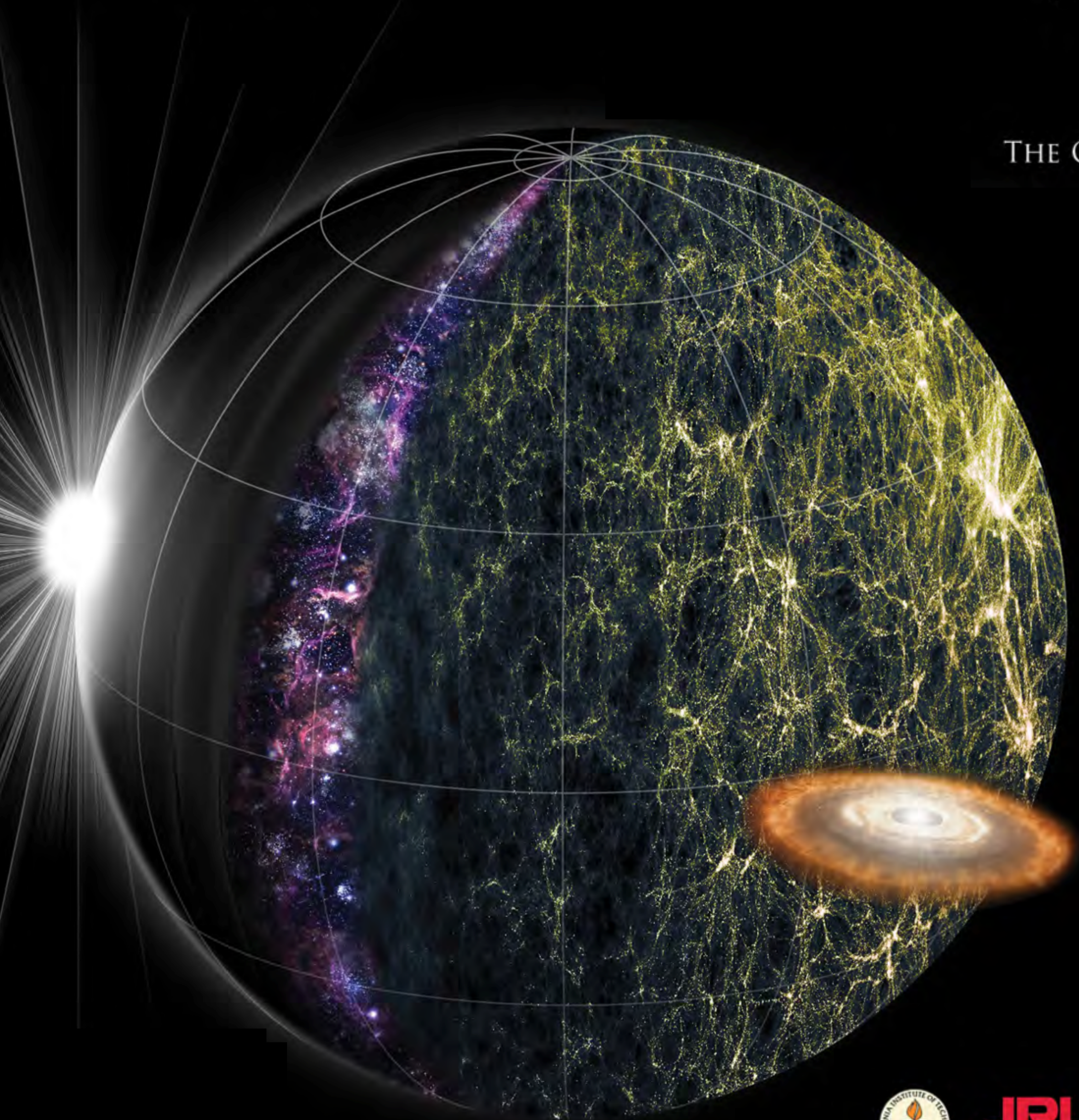
An All-Sky Spectral Survey

DESIGNED TO EXPLORE:

THE ORIGIN OF THE UNIVERSE

THE ORIGIN AND HISTORY OF GALAXIES

THE ORIGIN OF WATER IN PLANETARY SYSTEMS



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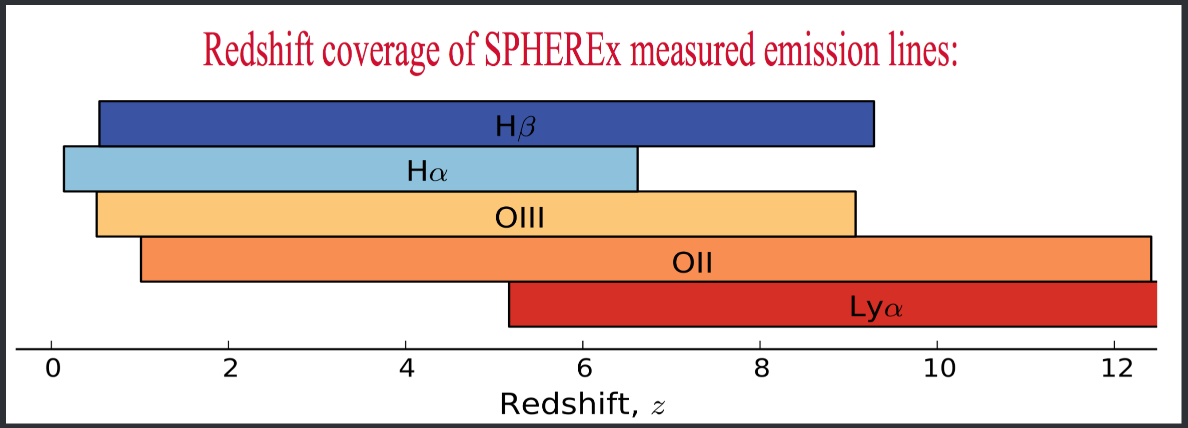
PS: O. Doré

http://spherex.caltech.edu

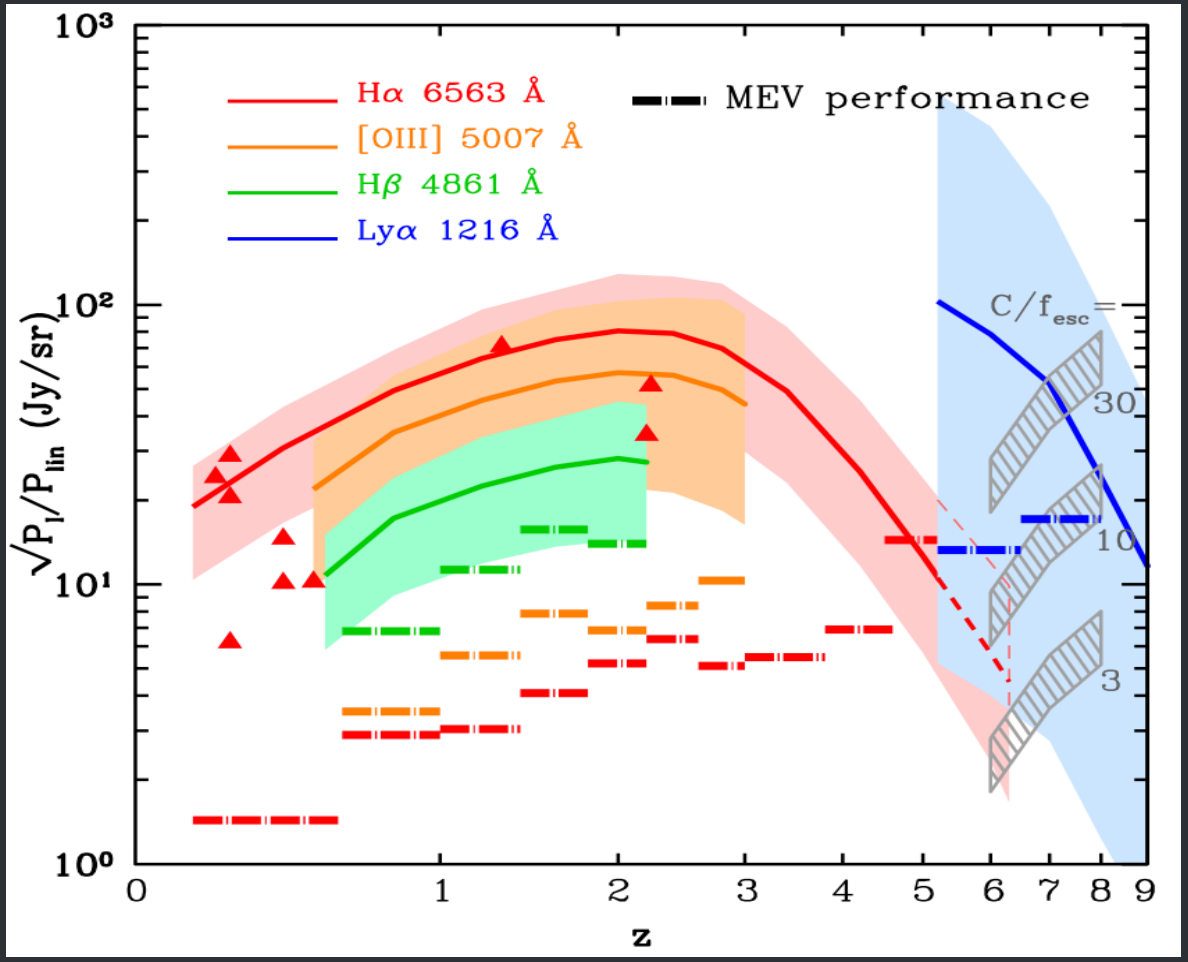
Jet Propulsion Laboratory
California Institute of Technology

Line Intensity Mapping with SPHEREx



Fluctuations in Line Emission

Clustering amplitude (bias)



Doré, Bock et al., arXiv:1412.4872

SPHEREx: low-resolution spectroscopic all-sky survey

For every ~6” pixel over the entire sky:

- **➡ R=40 spectra spanning (0.75 μm < λ < 4.81 μm).**
- **➡ R=150 spectra (4.1 μm < λ < 4.81 μm).**

- SPHEREx will measure 3D clustering of multiple line tracers at high SNR their luminosity-weighted biases.
- SPHEREx will map SFR throughout cosmic time
- SPHEREx might have sensitivity to detect Lya from EoR
- SPHEREx currently in MIDEX competition.

Summary

- Line Intensity Mapping offers an exciting and unique probe of a significant fraction of the Universe
- 21cm Intensity Mapping proof of concept demonstrated at z~0.8 (Chang et al. 2010).
  - 21cm IM at z~0.08 cross-power spectrum probes astrophysics (Anderson et al. 2017).
  - Opens up 21-cm 3D large-scale structure studies (GBT-HIM multi-beam array; HIRAX, CHIME, Tian-Lai in progress; and possibly SKA1-mid.)
- [CII] Intensity Mapping offers a complementary probe of the Epoch of Reionization
  - TIME will probe the [CII] source clustering at $6 < z < 9$. First light expected 2018.
- CO Intensity Mapping: a ~2-sigma detection at z=2-3 (Keating et al. 2016).
  - TIME will probe CO and infer molecular gas density at $0.5 < z < 2$.
- Lyman-alpha IM: a 3-sigma cross-correlation detection at z~2-3.5 (Croft et al. 2016).
  - SPHEREx may potentially probe Lya IM at z~6-8. HETDEX at z=2-3.
- EoR 21-cm detection may come from several groups with different approaches soon (LOFAR, PAPER, MWA). HERA/SKA1-LOW will bring next generation transformational sciences.